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THE EFFECT OF VARIATIONS IN CONTROLS AND DISPLAYS ON HELICOPTER INSTRUMENT APPROACH CAPABILITY

Frank R. Niessen, James R. Kelly, John F. Garren, Jr., Kenneth R. Yenni, and Lee H. Person

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16. Abstract

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SUMMARY

A flight investigation was conducted with a variable stability helicopter to determine the effects of variations in controls and displays on helicopter instrument approach capabilities. The baseline instrument approach task was a decelerating approach to a hover along a 6° glide slope. Pilot evaluations were obtained for both the constant-speed part of the task and the deceleration and hover part of the task. The variable stability capability of the research helicopter was used to provide three levels of control system sophistication: an attitude control augmentation system (CAS), an attitude stability augmentation system (SAS), and a rate SAS system. The CAS system was implemented by using a high-gain control technique, whereas the two SAS systems were implemented by using the response feedback method. In addition, the baseline display system was used both with and without three-cue flight director command information.

It was found that regardless of task or display configuration, the attitude SAS control system was strongly preferred over rate SAS, primarily because, even with the rate SAS, the aircraft had a divergent pitch response. From a display variation standpoint, it was not possible to decelerate to a hover in a consistent manner, regardless of the control system employed, with situation information only. In particular, the deceleration and hover task was unacceptable without flight director command information.

INTRODUCTION

Helicopters have been found to be useful for a variety of applications because of their ability to hover and, thus, to operate into confined areas and into remote sites without runways. However, this unique capability of the helicopter cannot presently be utilized under poor visibility conditions because of inadequate controls and displays. The task of flying a helicopter instrument approach to a hover poses a rather difficult control problem because of the requirement to control ground speed as a function of distance during the deceleration and the requirement to control position in a hover. A number of flight investigations have been conducted with regard to this particular task, but these investigations have, for the most part, concentrated on using only a single control-display configuration. In the investigation reported in reference 1, it was shown that it was possible to perform a decelerating instrument approach to a hover with a helicopter. The control-display system which was used consisted of an attitude CAS and a display system with a three-cue flight director.

As reported in reference 2, the same control-display system was used to investigate steep approach angles and various deceleration profile shapes.

The flight investigation described in this report was conducted in order to better understand the relative capabilities, limitations, and benefits associated with various control and display system combinations. For the instrument approach task of decelerating to a hover along a 6° glide slope, variations were made from the baseline control and display system used in the previous investigations. (See refs. 1 and 2.) The variable stability capability of the research helicopter was used to provide three levels of control system sophistication: an attitude CAS, an attitude SAS, and a rate SAS. The CAS system was implemented by using the high-gain model-following control technique, whereas the two SAS systems were implemented by using the response feedback method (ref. 3). In addition, the baseline display system was used both with and without the flight director command information. The various control and display system combinations were compared from the standpoint of approach and hovering performance and by pilot evaluation. Pilot comments and ratings were obtained for both the constant-speed part of the task and the deceleration and hover part of the task.

DESCRIPTION OF EQUIPMENT

Research Helicopter

The research helicopter which was used in the flight investigation is shown in figure 1. This helicopter was modified for control and display research by providing the evaluation pilot with both a variable stability control system and with primary electromechanical displays which could be driven by onboard general purpose analog computers.

The variable stability control system was achieved by removing the mechanical linkages connecting the evaluation pilot's controls, located on the right-hand side of the cockpit, and by installing electrohydraulic actuators for each control axis (pitch, roll, yaw, and collective). These actuators were installed in parallel with the safety pilot's controls, which were unaltered, so that his controls followed the control-surface motions resulting from electrical inputs. The onboard general purpose analog computers processed electrical signals from transducers on the evaluation pilot's controls and from other sensors, and thereby provided the electrical input signals to the actuators.

The display panel for the evaluation pilot is shown in figure 2. The attitude director indicator and the horizontal situation display were modified so that they could be driven by the onboard general purpose analog computers. The simulated radar altimeter, which featured an expanded scale for the last 30.5 m (100 ft) of altitude, was also driven by the analog computers. The mechanical collective position indicator displayed the position of the safety pilot's collective control. This instrument was used as a power indicator since a torquemeter was not installed. The remaining display indicators were conventional aircraft indicators.

Precision Radar

Aircraft position information was provided by a precision tracking radar system located at Wallops Flight Center, Virginia, where the flight tests were performed. The position of the aircraft was sensed in terms of slant range and azimuth and elevation angles. The position information was converted into rectangular coordinates in the runway reference frame and was then transmitted to the aircraft over an FM (frequency modulated) telemetry link. The radar was K-band and had an antenna beam width of 0.5°. The tracking-angle coverage of the radar was between 0° and 30° in elevation and $\pm 45^{\circ}$ in azimuth. The accuracy of the radar was 0.02° for the azimuth and elevation angles and 3 m (10 ft) or 1 percent, whichever was greater, for slant range.

Navigation Computer

Onboard the aircraft, an analog computer was used to smooth the radar position signals and to derive ground-referenced velocity information. This function was accomplished by using a complementary filtering technique that continuously mixed the radar position signals with acceleration information, which was derived from onboard instrumentation. This technique, described in reference 4, provided essentially noise-free position and velocity information without introducing any lag.

CONTROL SYSTEM

Control System Configurations

Three different control system configurations, representing three different levels of control system sophistication, were implemented for evaluation purposes. These systems will each be discussed in a separate section. Note that the aircraft's collective response was not varied during this investigation, and that the evaluation pilot was provided simply with the collective response characteristics of the unaugmented basic aircraft. The collective control sensitivity was approximately -0.0856 g/cm (-0.22 g/in.), and the vertical damping-to-mass ratio was approximately -0.5 sec^{-1}.

Rate SAS system.- For the rate SAS configuration, rate damping augmentation was provided in pitch, roll, and yaw. Augmentation was achieved by using the response feedback method; that is, the actuator command signal was formed by summing the rate gyro signal with the pilot's control input signal. For the yaw axis, a body-mounted lateral accelerometer signal was also included to augment static directional stability. Although conventional SAS actuators generally have limited actuator authority, this factor was not included in the present investigation since it would not be expected to have much effect on an instrument flight task where only mild maneuvering would be required.

The rate SAS gains, in terms of the deflection of the safety pilot's control due to each of the input signals, are given in table I. The sensitivity of each of the evaluation pilot's controls was set equal to that of the basic aircraft, and the levels of artificial rate damping and directional stability were

established according to pilot preference during a series of preliminary flights. Approximate control sensitivities and stability derivatives for the augmented aircraft, as shown in table II, were computed based on the SAS gains in table I and stability derivative data for the basic aircraft from table IV-12 of reference 5. The levels of control sensitivity and rate damping are in excess of the minimum requirements set forth in reference 6. Based on the augmented stability derivatives, the characteristic roots for both the longitudinal and the lateral-directional dynamics were computed for the augmented aircraft. These roots are presented in table III. It can be seen that an unstable real root exists for the longitudinal dynamics at speeds of 40, 60, and 80 knots, and indicates a pure divergent longitudinal mode. This root represents a rapid divergence with a time to double amplitude less than 3 seconds. This mode results primarily from the static instabilities of the basic aircraft with respect to both angle of attack and speed. It is interesting to note that according to the longitudinal dynamic stability criteria from reference 6, a positive real root with a value of more than 0.15 (time to double amplitude of approximately 5 seconds or less) is considered to be unacceptable.

Attitude SAS system.- The attitude SAS system was implemented in the same way as the rate SAS system, except that attitude feedback signals were also included in pitch and roll. The control sensitivities and rate damping characteristics were kept the same as those for the rate SAS system. For both the attitude SAS system and the rate SAS system, the yaw modes were identical. The attitude SAS gains, listed in table I, were also established according to pilot preference during a series of preliminary flights. The stability derivatives for the augmented aircraft are presented in table II, whereas the characteristic roots of the augmented aircraft are presented in table III.

Attitude CAS system.- The attitude CAS configuration was implemented by means of a high-gain model-following control technique which is described in detail in the appendix. This control technique, in contrast to the response feedback method, effectively suppressed the stability characteristics of the basic aircraft and heavily suppressed the response of the aircraft to gusts for the angular degrees of freedom. The attitude CAS configuration represented the same control concept which had been employed previously in the investigations reported in references 1 and 2. Pitch and roll attitude were commanded by the position of the pilot's control stick. In yaw, the pilot could select either a turn-following or a heading-hold mode. In the turn-following mode, automatic turn coordination was provided. In the heading-hold mode, magnetic heading was automatically maintained when the pedal input was within a small deadband region. Outside of that deadband, the pilot input commanded turn rate. The control response characteristics for the attitude CAS system are presented in table IV.

Controller Characteristics

The force-feel characteristics of the evaluation pilot's controls are described in this section. One set of characteristics was used for each control system. Linear force gradients of 1.8 N/cm (1 lb/in.) were provided in pitch and roll and 8.8 N/cm (5 lb/in.) in yaw; the breakout forces were negligible. Also, the center stick and pedals could be force-trimmed by means of beeper switches. Dashpots were added to the center stick for pitch and roll and

resulted in a damping ratio of approximately 0.7 for the unforced stick response. The pilots commented that this modification to the feel system resulted in a very significant control system improvement as compared with the feel system used in previous investigations where the center stick had almost no damping. Lastly, the evaluation pilot's collective stick was provided with an adjustable friction device.

DISPLAY SYSTEM

The two display configurations which were used for evaluation purposes are referred to herein as the flight director and the situation-only display configurations. The flight director display configuration was identical to the display configuration which had been used in previous investigations (refs. 1 and 2). The situation-only display configuration was the same, except that the three flight director commands on the attitude director indicator were driven out of view. As pointed out earlier, the onboard analog computers were used to drive the primary display indicators - the attitude director indicator and the horizontal situation display. Each of these is described in the following sections.

Attitude Director Indicator

The attitude director indicator is shown in detail in figure 3. The pitch command was used to maintain range rate or speed; the roll command, cross range; and the collective command, altitude. The nominal range-rate and altitude profiles, which were functions of range, are presented in figure 4. The range-rate profile caused the helicopter to come to a hover from an initial speed of 50 knots. The deceleration rate varied from approximately 0.08g at the beginning of the deceleration to approximately 0.04g at the end. This deceleration profile nominally required a constant helicopter pitch attitude 1° above that for hover, for a no-wind condition. The altitude profile featured a 6° glide slope to a 15.2-m (50-ft) altitude at the hover point. The flight director control laws are shown in block diagram form in figure 5. The flight director system, when compared with that used for previous investigations (refs. 1 and 2), featured somewhat lower gains and a milder deceleration profile. "Fly-to" sensing was employed for each of the commands; for example, the pitch command bar was deflected upward for a pitch-up command. This type of sensing has been consistently preferred by pilots who have participated in previous helicopter control-display investigations at the Langley Research Center (for example, refs. 1 and 2).

The altitude error and cross-range error indicators, shown also in figure 3, had full-scale values of ± 30.5 m (± 100 ft) and ± 45.7 m (± 150 ft), respectively. The rising runway symbol (fig. 3) displayed altitudes from 30.5 m (100 ft) to touchdown.

Horizontal Situation Display

The horizontal situation display, shown in figure 6, provided heading, range, and cross-range information. Although two heading display modes were available, a north-up mode and a heading-up mode, the pilots had a strong preference for the heading-up mode and used it exclusively. This mode was an "inside-out" mode where the aircraft heading could be read at the top of the display and where crab angle was indicated by the angle between the runway heading and a line extended through the fixed aircraft symbol.

Range and cross-range information were indicated by the position of a moving runway relative to the fixed aircraft symbol. Three charts, shown in figure 7, were used to provide a symbolic runway at three difference scales - 120 m/cm (1000 ft/in.), 40 m/cm (333 ft/in.), and 12 m/cm (100 ft/in.). Automatic switching between charts occurred at ranges of 1830 m (6000 ft) and 610 m (2000 ft).

CONDUCT OF THE TEST

Task Description

The following procedure describes the approach task which was used for evaluation purposes. Control of the aircraft was transferred to the evaluation pilot with the aircraft headed outbound on the approach center line prior to reaching 1220-m (4000-ft) range. At the time of control transfer, the aircraft was either in level flight or in a slight climb at an altitude of 61 m (200 ft) or more, with an airspeed of approximately 50 knots. The evaluation pilot followed the runway center line outbound by using the horizontal situation display. At 1520-m (5000-ft) range, the aircraft was turned to intercept and track a teardrop pattern (dotted line) all the way around and back to the runway center line. (See fig. 7.) The radius of the circular section of this pattern was 760 m (2500 ft). During this time, the pilot was to fly the aircraft to 244-m (800-ft) altitude and maintain airspeed at approximately 60 knots. For the flight director display configuration, the commands were turned on once the runway center line had been intercepted. The pitch and roll commands were usable immediately, but the collective command was not usable until the glide slope was intercepted at a range of about 2130 m (7000 ft). For the situation-only display configuration, flight director commands were not displayed. In either case, the task was the same - to fly the aircraft along the prescribed flight path to a stabilized hover over the pad. The pilots were each instructed to maintain a level of performance consistent with a realistic operational environment.

Test Conditions

Pilot evaluations were obtained for six control-display configurations, formed by combining each of the three control system variations with each of the two display system variations. These configurations are shown in matrix form in figure 8.

The flight investigation was conducted with two evaluation pilots who were given approximately equal amounts of time with each configuration. Both were helicopter, as well as fixed-wing, pilots, and each had extensive instrument flight experience in fixed-wing aircraft. In addition, one of the pilots was formerly a Navy antisubmarine warfare (ASW) helicopter pilot. Both pilots had participated in a variety of instrument flight research projects at NASA involving helicopters, V/STOL aircraft, and fixed-wing aircraft.

The pilot evaluations were obtained over a 3-week period during which 13 flights were conducted. For the first series of flights, the variations in controls and displays proceeded in the order of increasing sophistication (that is, I, II, III, etc.), and then this order was reversed for the last series of tests. The first two flights were devoted mostly to pilot familiarization with the rate SAS control system configurations. Generally, however, a flight consisted of two or three approaches for each of either two, three, or four control-display configurations. After every flight or two, the other evaluation pilot would repeat the same set of test conditions. Over the course of the flight investigation, each pilot flew a minimum of six approaches for each control-display configuration.

A variety of wind conditions were encountered during the flight-test program. The wind magnitude and direction are presented for each flight in table V. It can be seen that for a number of flights, strong cross winds and/or tail winds were present.

RESULTS AND DISCUSSION

Performance

Approaches.- Composite plots of range rate, altitude, and cross range against range for each control-display configuration are presented in figure 9. It can be seen that the approach performance achieved was largely independent of the control system variations and was considerably better with the flight director display than with the situation-only display. Although the altitude and cross-range tracking errors were considerably larger with the situation-only display configuration, it should be noted that the pilots considered this performance to be adequate.

Deceleration and hover.- The plots of range rate against range for the situation-only display configurations reflect inconsistent performance for the deceleration and hover part of the task. Because of particular interest in the ability to hover, a limited number of special hovering tests were also conducted. For these tests, the task was simply to maintain a hover over the pad at a constant altitude of 15 m (50 ft). Only the attitude CAS control system was used in these tests. The task began with the helicopter already in a hover over the pad. At first, the evaluation pilot was provided the flight director display; then, after about 1 minute, the flight director commands were removed. The hovering performance with each of these displays is shown in figure 10. The aircraft could be kept within 7.6 m (25 ft) of the center of the pad indefinitely with the flight director display, but once the flight director command information was removed, the aircraft began to slowly diverge, in an oscillatory manner,

from the desired position. The length of time for each of the runs, after the flight director commands were removed, is indicated in the figure.

Pilot Technique

Approaches.- Two notably different piloting techniques resulted for the two display variations. With the flight director display, the pilots would continually make small changes in attitude or collective as they followed the command needles. With the situation-only display, however, the pilots used what they described as a "bang-bang" control technique. For example, they would normally maintain a wings-level roll attitude, but, whenever the cross-range error and/or heading deviation built up, the pilots would then maintain a constant roll attitude of, for example, from 3° to 5° until the situation was corrected. At that time, the normal wings-level roll attitude would be resumed. The same kind of technique was used to control airspeed by using pitch attitude and to control altitude by using vertical speed (via collective inputs). This bang-bang control technique was definitely a single-axis type of control technique which generally was useful only for making corrections one at a time.

Deceleration and hover.- The preceding discussion applies as well to the task of decelerating to, and maintaining, a hover. This task was considerably more demanding, primarily because the range rate needed to be controlled as a function of range for the deceleration, and position as well as velocity had to be maintained in the hover. With the situation-only display, the following information was available: pitch attitude, indicated airspeed (which was usable down to an airspeed of about 30 knots), and range information via the horizontal situation display. And, with the fine-scale chart, the rate of movement of the runway symbol provided a useful range-rate cue. Although the bang-bang control technique was surprisingly effective, in many instances, in bringing the helicopter close to a hover near the pad, a hover could not, in fact, be maintained. The single-axis nature of the pilot's control technique was revealed spectacularly in one of the hover tests in which the helicopter climbed to an altitude over 180 m (600 ft) while the pilot was concentrating on controlling horizontal position.

Curved-path tracking.- As described in a previous section, the preliminary part of the approach task involved the tracking of a teardrop pattern by means of the horizontal situation display. Flight director commands were not provided for this task. Interestingly, the technique which the pilots preferred to use was not to hold a constant bank angle, but rather to fly a series of headings tangential to the desired path. (At a nominal speed of 60 knots, a constant bank angle of 7° would have been required to stay on the circular section of the curved path.) With the horizontal situation display, the pilots always knew the aircraft position and heading relative to the desired path; thus, curved-path tracking was accomplished relatively easily with this control technique.

Summary of Pilot Comments

Controls.- With the rate SAS control system, with either display, instrument flight was possible but was not considered practical. The tendency of the

aircraft to diverge in pitch was a problem even with the level of artificial rate damping that was provided. So much attention was required to maintain basic attitude control that not enough time could be spent on the approach tracking task. The pilot indicated that his workload was at 100 percent with the rate SAS control sytem with either display. On one approach, while the pilot was concentrating on capturing the runway center line, the pitch attitude diverged to 30° noseup before a recovery could be made. Since both airspeed and altitude errors would result from pitch-attitude excursions, the pitch divergence tended to make the tracking task especially difficult.

The attitude SAS control system was a vast improvement over rate SAS. With attitude stability, the aircraft could be trimmed for hands-off flight. Some attention was still required for precise attitude control, since trim changes were noticeable with power and attitude changes in response to gust disturbances were apparent. With a more relaxed attitude control task, the pilot was able to function more as a manager with regard to the tracking task. Enough time was now available to adequately cross-check situation information. For example, the pilot was better able to recognize a cross-wind situation and to establish the proper crab angle; also, he was able to recognize the combined effect of pitch and collective inputs on airspeed and altitude.

Although the attitude CAS control system was an improvement over attitude SAS, it was not nearly as much an improvement as attitude SAS compared with rate SAS. The high-gain attitude CAS system masked the basic aircraft trim characteristics and essentially eliminated any attitude response to gust disturbances. These features resulted in a further decrease in pilot control activity. With the flight director display, this system resulted in a very low pilot workload; the physical workload was so low that it was possible to fly an entire approach with the trim button only.

The resistance of each of the control systems to external disturbances was reflected by the flight director display, as the flight director commands were noticeably more active with the least sophisticated control systems. For the rate SAS and attitude SAS systems, this activity caused the pilots to be somewhat reluctant in answering the flight director commands. With the attitude CAS system, however, the pilots did not hesitate to answer the commands.

Displays.- The horizontal situation display, which provided aircraft range, cross range, and heading information, was generally considered to be a very good situation display. Although the rate of movement of the runway symbol provided a useful range-rate cue for the deceleration, adequate velocity information for hovering could not be derived from the horizontal situation display. Also, the switching between charts, which resulted in an abrupt change in chart scale factors, was found to be somewhat distracting when it occurred. A gradual change in scale factor, which would have been possible with an electronic display, would have been preferred. Lastly, although crab angle was apparent by the difference between aircraft heading and that of the runway symbol, one pilot noted that, in addition, a runway heading reference mark on the compass card would have facilitated a more precise determination of crab angle.

The pilots commented that they made very little use of the cross-range error indicator on the attitude director indicator because the same informa-

tion was presented on the horizontal situation display in a superior way. Also, the rising runway symbol on the attitude director indicator was also rarely used in lieu of the radar altimeter display. This was primarily because the radar altimeter could be used during the entire approach, whereas the rising runway symbol only appeared after the aircraft descended below 30.5 m (100 ft).

Although the same flight director control laws were used with each of the control system variations, the flight director commands were found to be acceptable with each of the control systems.

With the flight director display and either attitude SAS or attitude CAS, the pilots were able to monitor and cross-check situation information sufficiently. And, with these control systems, the pilots commented that they were able to maintain about the same level of awareness of the situation with the flight director display configuration as they were with the situation-only display.

With the rate SAS control system, the flight director was found to be particularly useful for attitude control as well as for guidance. The flight director provided acceptably small attitude commands for the approach tracking task, and by satisfying these commands, the pilot was able to maintain control of attitude as well. For the rate SAS control system, the addition of the flight director display was a vast improvement over the situation-only display. The small tracking errors and mild attitudes which resulted with the flight director display configuration did much to alleviate pilot workload, especially apprehension, with the rate SAS control system. Also, when the flight director display was used with the rate SAS control system, the pilots commented that more time could be devoted to situation information. However, even though decelerations to hover could be consistently achieved with the rate SAS and flight director configuration, the pilot still had to concentrate too much on attitude control (via the flight director commands as well as the attitude indicator), and the pilot workload was still considered to be unacceptably high.

The use of the flight director for attitude control was also illustrated very unexpectedly when loss of artificial pitch-rate damping occurred during an approach with the attitude SAS and flight director configuration. With attitude stiffness, but without rate damping, the pitch response became quite underdamped and oscillatory. However, by simply keeping the flight director commands centered, a well-controlled, decelerating approach to hover was completed successfully.

A number of general comments were obtained relative to the use of the flight director display as compared with the situation-only display. As pointed out earlier, the pilots used considerably different control techniques with each of these two display configurations. Although it was recognized that the approach performance was better with the flight director, the pilots considered the approach performance adequate with the situation-only display, excluding the deceleration and hover task. The pilots liked the feature of being able to make the control decisions themselves, when this was possible, with the situation-only display. With the flight director display, however, the flight director commands were found to be very compelling and could not be ignored, or even treated as secondary information. A main drawback to the situation-only display

was that it was difficult to make large, simultaneous corrections which were sometimes necessary during the final approach. On the other hand, with the flight director display, large simultaneous corrections could be made without any difficulty.

Pilot Ratings

Numerical pilot ratings, based on the rating scale suggested in reference 7, were obtained for each of the control-display configurations. The pilot ratings presented herein were obtained by averaging the individual pilot ratings, which were substantially in agreement. These ratings were obtained in order to quantify the pilot comments discussed in the previous section. It is emphasized that a number of complex, interrelated factors were involved in arriving at each of these ratings. In order to sort out the effects of the deceleration and hover part of the task, a second set of pilot ratings was obtained for the constant-speed part of the approach task excluding the deceleration and hover.

The pilot ratings that were obtained for the approach task including the deceleration and hover are presented in figure 11. For this task, a substantial difference in pilot ratings was obtained with the display variations. For a given display, the rate SAS control system was rated much lower than either the attitude SAS or the attitude CAS control system. The attitude SAS and attitude CAS configurations were rated unacceptable with situation information only because the task could not be completed. With the rate SAS and flight director configuration, although the task could be completed, the level of pilot workload required was not tolerable.

Ratings for the approach task excluding deceleration and hover are presented in figure 12. All these ratings show an improvement over those obtained for the complete task. Note that with this task, there is relatively little difference with the display variations, except for rate SAS. Here again, the flight director commands were especially helpful with the attitude control task.

Effect of Adverse Winds

With the yaw control systems employed for either the rate SAS, the attitude SAS, or the attitude CAS/turn-following configurations, the aircraft tended to point into the wind. This tendency would normally be desirable, of course, but deficiencies in the flight director control laws would have resulted in improper commands if the aircraft were permitted to head into a cross wind or a tail wind. (Since the pitch and roll flight director commands were not resolved as a function of heading, these commands were valid only when the aircraft heading was within approximately 30° of the runway heading.) In the presence of a cross wind or tail wind, when the pilot tried to keep the aircraft heading lined up with the runway heading, his workload became very high because of the additional control task. Furthermore, in the case of a cross wind, with the aircraft banked into the wind, the resulting side force would induce pilot vertigo and was found to be intolerable for bank angles of 5° or more. The attitude CAS heading-hold feature relieved the task of maintaining heading, but still suffered the same bank-angle limitation from the standpoint of pilot vertigo.

CONCLUSIONS

A flight investigation was conducted with a variable stability helicopter to determine the effects of gross variations in controls and displays on helicopter instrument approach capabilities. On the basis of that investigation, the following conclusions are drawn:

1. Regardless of task or display configuration, the attitude stability augmentation system (SAS) control system was a vast improvement compared with rate SAS, primarily because the aircraft/rate SAS system had a divergent pitch response. With rate SAS, the pilot was so involved with controlling attitude that tracking of center line and glide slope was considered a task of secondary importance. With attitude stabilization, the pilot was relieved enough from the basic attitude control task that he was able to spend much more time on the tracking task and be more of a manager.

2. It was not possible to decelerate to a hover in a consistent manner, regardless of the control system employed, with situation information only. The deceleration and hover part of the task was unacceptable without command information.

3. With situation information only, the constant-speed part of the approach task could be performed satisfactorily with either the attitude SAS or the attitude control augmentation system (CAS). With rate SAS, the pilot workload was so high that this configuration was considered to be unacceptable.

4. Command information was especially useful with the rate SAS control system because the task of controlling attitude, as well as the approach tracking task, was accomplished by centering the flight director commands. Nevertheless, the lack of attitude stability resulted in a high pilot workload, as any additional task or distraction beyond centering the flight director commands and monitoring situation information would have permitted pitch attitude to diverge.

5. The use of attitude CAS instead of attitude SAS resulted in some improvement in lowering control activity, but was not nearly as much an improvement as attitude SAS compared with rate SAS. Basic aircraft cross-coupling and trim characteristics, as well as light to moderate turbulence which was encountered during several of the flights, were factors which contributed to the pilots appreciation of differences between attitude SAS and attitude CAS.

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APPENDIX

CONTROL AUGMENTATION SYSTEM IMPLEMENTATION

The model-following control system used for pitch and roll is shown in figure 13. The model response (including angular acceleration, angular rate, and attitude) was computed on the basis of the pilot's control input only. The inherent angular rate damping characteristics of the basic aircraft were approximately canceled by an unstable rate-gyro feedback term. This cancellation was done to provide an approximately neutral system to simplify the control structure for the feed-forward term and to achieve higher gains in the closed-loop feedback terms. The feed-forward term was used as a lead term to provide the proper initial response. In fact, if the system were perfectly neutral, the feed-forward term would have provided the exact response by itself. Angular rate error and attitude error terms represented the differences between the model response and the actual helicopter response. These terms were used as high-gain closed-loop control terms to force the helicopter to follow the model, and thereby overpower any remaining basic aircraft stability and control characteristics or any response that might be caused by external disturbances such as gusts. The closed-loop error gains that were used resulted in a bandwidth for the plant several times that of the model response. These gains were sufficiently high that it was not considered necessary to include an integrated attitude error term.

The model-following control system for yaw is shown in figure 14. For the turn-following mode only, the model roll attitude, model roll rate, and lateral accelerometer terms were also included as inputs to the model yaw response. When the pilot changed heading modes, these terms were switched in or out through a special circuit which eliminated any transient. The model roll attitude and model roll rate terms were used to eliminate sideslip in the turn-following mode. The gains for these terms were based on a nominal speed of 45 knots. The lateral accelerometer was included to provide additional closed-loop compensation to minimize sideslip. The gain on the lateral accelerometer was set to provide the desired level of directional stability at, again, a speed of 45 knots. Because the lateral accelerometer output was more sensitive to sideslip at higher speeds, the level of directional stability actually increased somewhat with speed. This rather simple approach to automatic turn coordination was found to be very effective over the speed range for which it was used - from hover to 80 knots airspeed. The inherent damping of the unaugmented aircraft was so low in yaw that the aircraft was assumed to be neutral without any unstable yaw rate feedback term. The lead term and the high-gain rate error term were used as with pitch and roll. For turn-following and for heading hold when the pedals were outside the deadband, a heading error term was computed by integrating the yaw rate error. When heading hold was selected and the pedals were inside the deadband, this integration output was held constant, and heading error was obtained from a directional gyro with a synchronizer circuit.

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6. V/STOL Handling - Qualities Criteria. I - Criteria and Discussion. AGARD Rep. No. 577, 1970.

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TABLE I.- RATE AND ATTITUDE SAS GAINS

[Gains are given in terms of the deflection of the safety pilot's control due to each of the input signals]

Rate SAS:	
Pitch:	
Evaluation pilot's control, cm/cm (in./in.)	1.0 (1.0)
Angular rate, cm/rad/sec (in./rad/sec)	-13.3 (-5.25)
Roll:	
Evaluation pilot's control, cm/cm (in./in.)	1.0 (1.0)
Angular rate, cm/rad/sec (in./rad/sec)	-7.92 (-3.12)
Yaw:	
Evaluation pilot's control, cm/cm (in./in.)	1.0 (1.0)
Angular rate, cm/rad/sec (in./rad/sec)	-22.4 (-8.80)
Lateral acceleration, cm/m/sec^2 (in./ft/sec^2)	-4.05 (-0.486)
Attitude SAS:*	
Pitch:	
Pitch attitude, cm/rad (in./rad)	-20.2 (-7.95)
Roll:	
Roll attitude, cm/rad (in./rad)	-8.56 (-3.37)

*Same as for rate SAS, plus the additional terms given.

TABLE II.- CONTROL SENSITIVITIES AND AUGMENTED STABILITY DERIVATIVES FOR THE RATE SAS AND ATTITUDE SAS CONTROL SYSTEMS

Airspeed, knots	Control sensitivity, $\frac{\text{rad/sec}^2}{\text{cm}}$	Control sensitivity, $\frac{\text{rad/sec}^2}{\text{in.}}$	Angular rate damping, sec^{-1}	Attitude stiffness, sec^{-2} (a)	Moment due to sideslip, $\frac{\text{rad/sec}^2}{\text{m/sec}}$	Moment due to sideslip, $\frac{\text{rad/sec}^2}{\text{ft/sec}}$
Pitch						
0	0.141	0.359	-2.64	-2.85		
20	.141	.359	-2.83	-2.84		
40	.156	.395	-3.35	-3.14		
60	.174	.442	-3.77	-3.51		
80	.185	.471	-3.97	-3.74		
Roll						
0	0.205	0.521	-2.23	-1.76		
20	.205	.521	-2.29	-1.75		
40	.202	.513	-2.36	-1.72		
60	.201	.510	-2.38	-1.73		
80	.201	.510	-2.35	-1.72		
Yaw						
0	0.080	0.203	-1.83		0.00886	0.00270
20	.080	.203	-1.81		.01814	.00553
40	.078	.199	-1.82		.02044	.00623
60	.078	.199	-1.82		.02415	.00736
80	.077	.195	-1.81		.02897	.00883

[a]Values indicated are for attitude SAS only. For rate SAS, these terms are zero.

TABLE III.- CHARACTERISTIC ROOTS FOR THE RATE SAS AND ATTITUDE SAS CONFIGURATIONS

Airspeed, knots	Longitudinal	Lateral-directional
	Rate SAS	
0	$0.0058 \pm j0.2739$ -0.3324 -2.6690	$0.0189 \pm j0.3686$ -1.8336 -2.2773
20	$-0.0045 \pm j0.2875$ -0.2719 -2.9728	$-0.0266 \pm j0.4658$ -1.7175 -2.3660
40	0.2674 $-0.2469 \pm j0.2641$ -3.6836	$-0.1029 \pm j0.4861$ -1.5983 -2.4349
60	0.2622 $-0.2910 \pm j0.2435$ -4.1570	$-0.2253 \pm j0.5399$ -1.3609 -2.4741
80	0.2327 $-0.3148 \pm j0.2081$ -4.3971	$-0.4361 \pm j0.6892$ -0.9104 -2.4955
	Attitude SAS	
0	-0.0942 -0.3355 $-1.2800 \pm j1.0031$	-0.2944 $-0.9728 \pm j0.5150$ -1.8330
20	-0.0740 -0.6607 $-1.2595 \pm j0.5180$	$-0.5499 \pm j0.5409$ -1.4279 -1.6089
40	0.0402 $-0.6396 \pm j0.5475$ -2.6711	$-0.5278 \pm j0.6729$ $-1.5917 \pm j0.2780$
60	0.0272 $-0.6463 \pm j0.6187$ -3.2115	$-0.5377 \pm j0.8527$ $-1.6051 \pm j0.3555$
80	0.0075 -0.6673 ± 0.6649 -3.4670	$-0.5483 \pm j1.0802$ $-1.5908 \pm j0.3936$

TABLE IV.- CONTROL RESPONSE CHARACTERISTICS FOR THE ATTITUDE CAS CONTROL SYSTEM

Pitch and roll:	
Control sensitivity, rad/sec^2/cm (rad/sec^2/in.)	0.079 (0.2)
Angular rate damping, sec^{-1}	-2.12
Attitude stiffness, rad/sec^2/rad	-2.0
Natural frequency, rad/sec	1.41
Damping ratio	0.75
Yaw (turn-following and heading-hold modes):	
Control sensitivity, rad/sec^2/cm (rad/sec^2/in.)	0.083 (0.21)
Control deadband, cm (in.)	±0.64 (±0.25)
Augular rate damping, sec^{-1}	-0.7
Yaw (turn-following mode only):	
Directional stability, rad/sec^2/rad	0.32
Yaw due to roll, rad/sec^2/rad	0.30
Yaw due to roll rate, rad/sec^2/rad/sec	0.43
Natural frequency, rad/sec	0.56
Damping ratio	0.62

TABLE V.- SURFACE WIND CONDITIONS

Flight number	Runway heading, deg	Wind direction, deg	Wind magnitude, knots
1	280	260	6 to 8
2	280	250	10 to 12
3	280	200	8 to 10
4	100	200	14 to 18
5	280	340	10 to 12
6	280	300	6 to 10
7	280	350	7 to 8
8	350	040	6 to 8
9	350	320	8
10	350	170	6 to 12
11	280	230	6 to 8
12	280	200	10 to 14
13	280	260	10 to 14

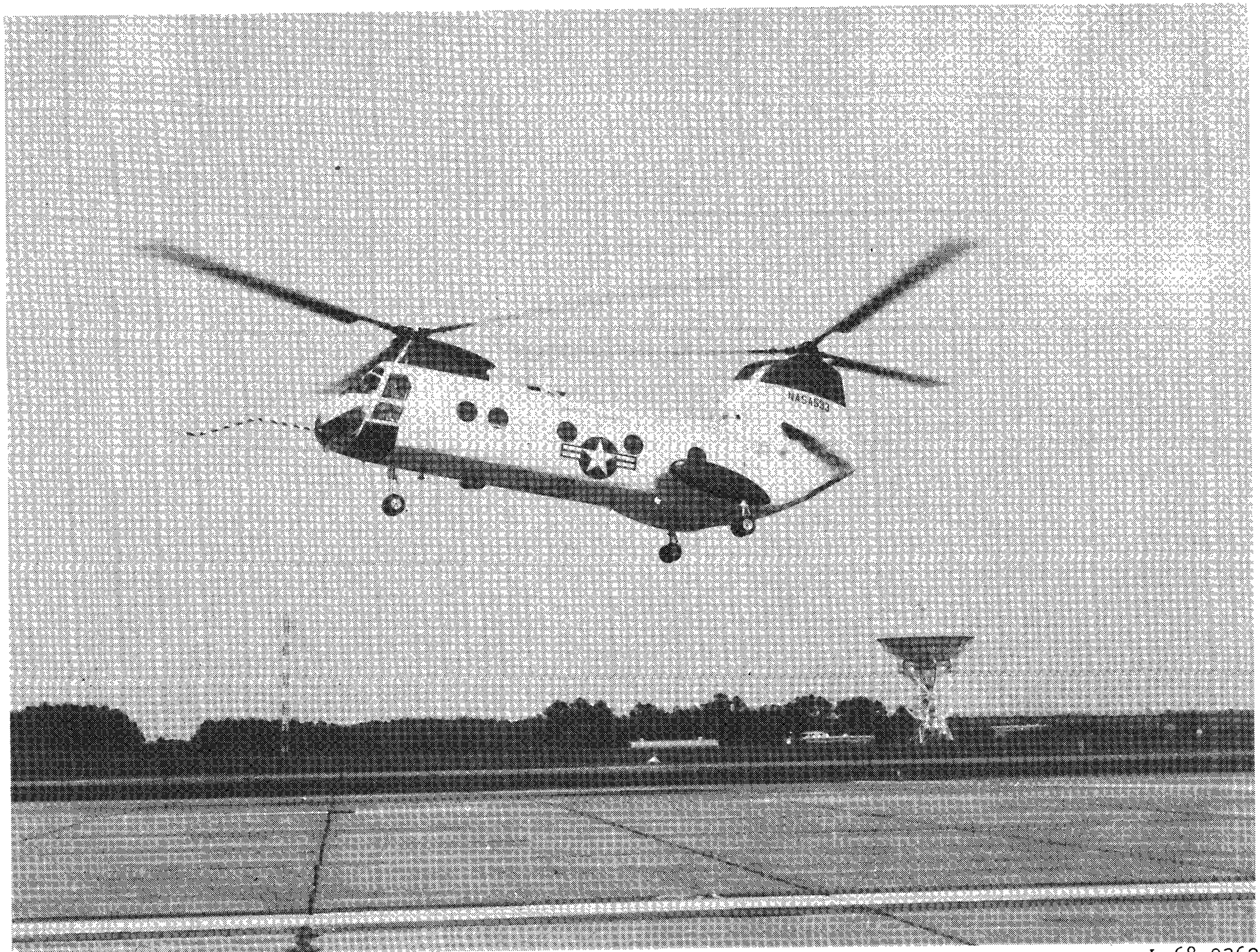

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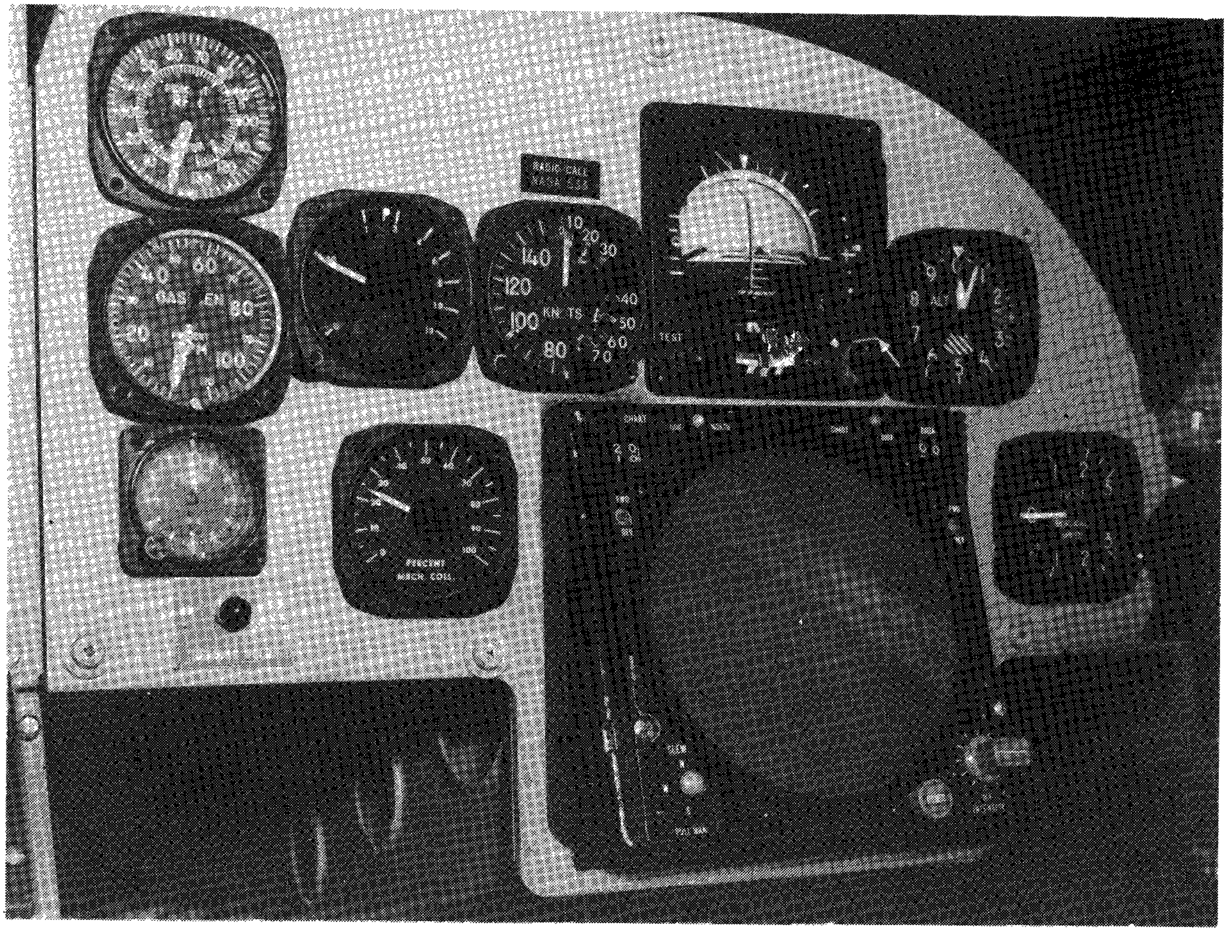
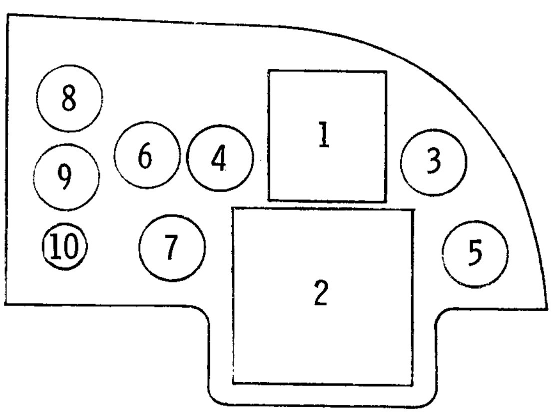
Figure 1.- Research helicopter.





1 Attitude director indicator
2 Horizontal situation display
3 Pressure altitude
4 Indicated airspeed
5 Vertical speed
6 Radar altitude
7 Safety pilot's collective position
8 Engine and rotor rpm
9 Compressor rpm
10 Clock

L-76-7511

Figure 2.- Display panel for evaluation pilot.

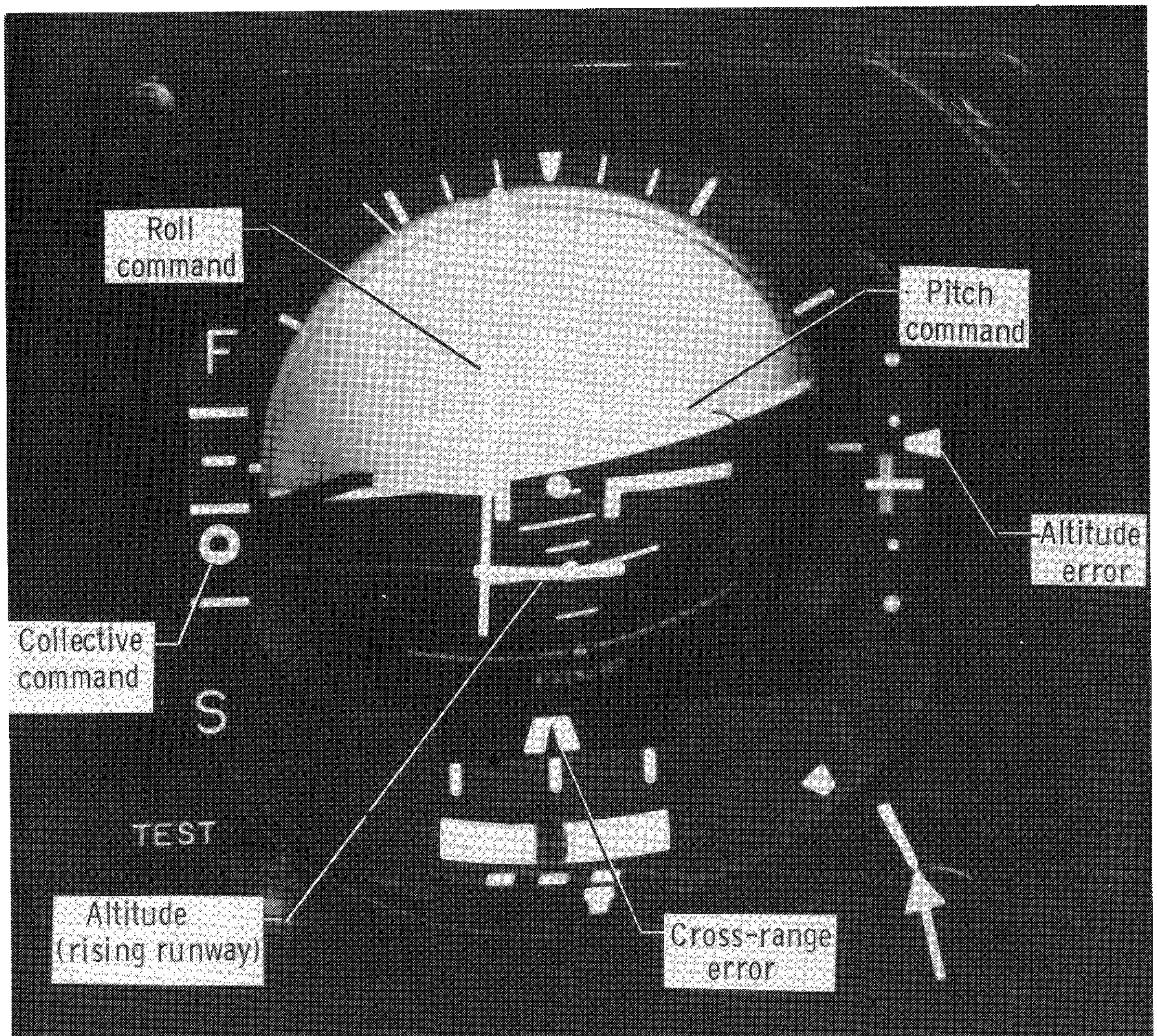


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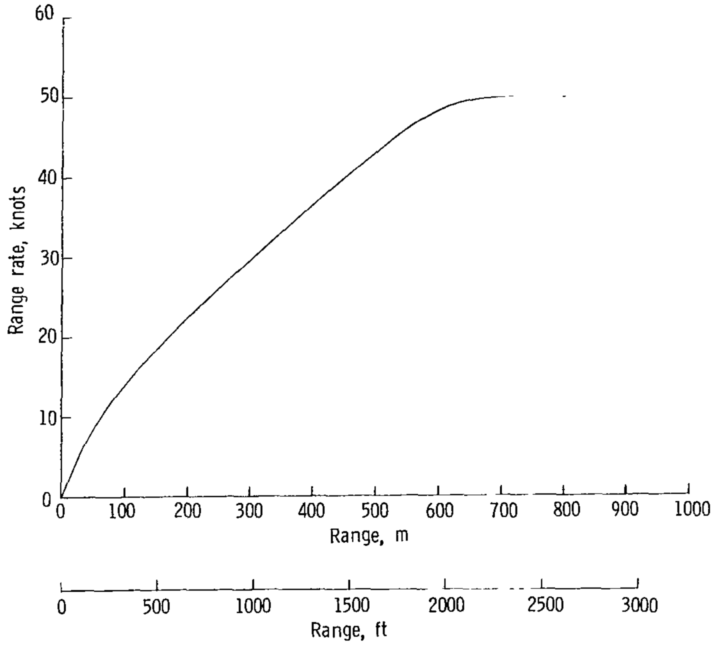
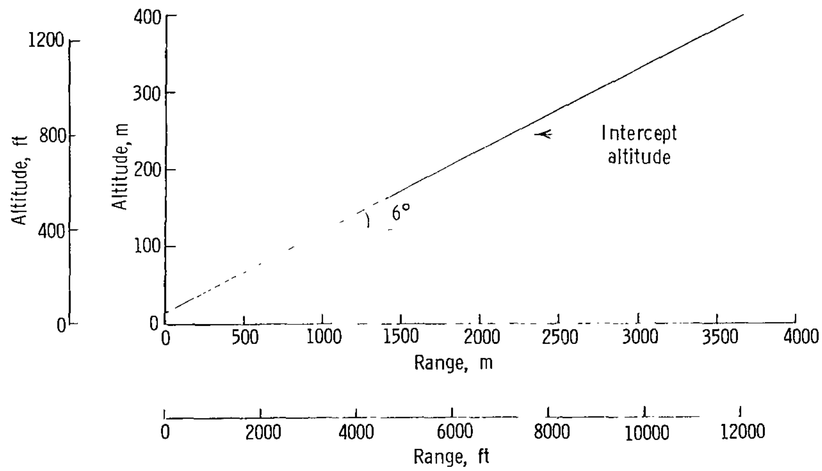
Figure 3.- Attitude director indicator.

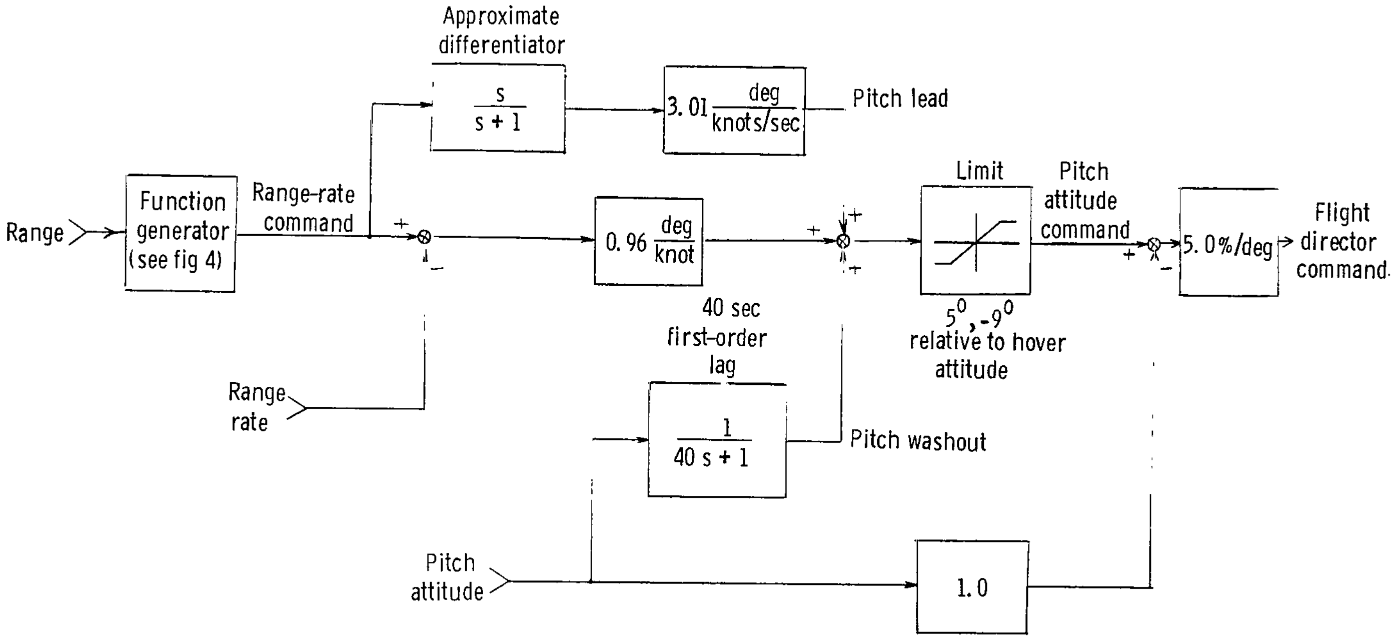


(a) Range-rate profile.



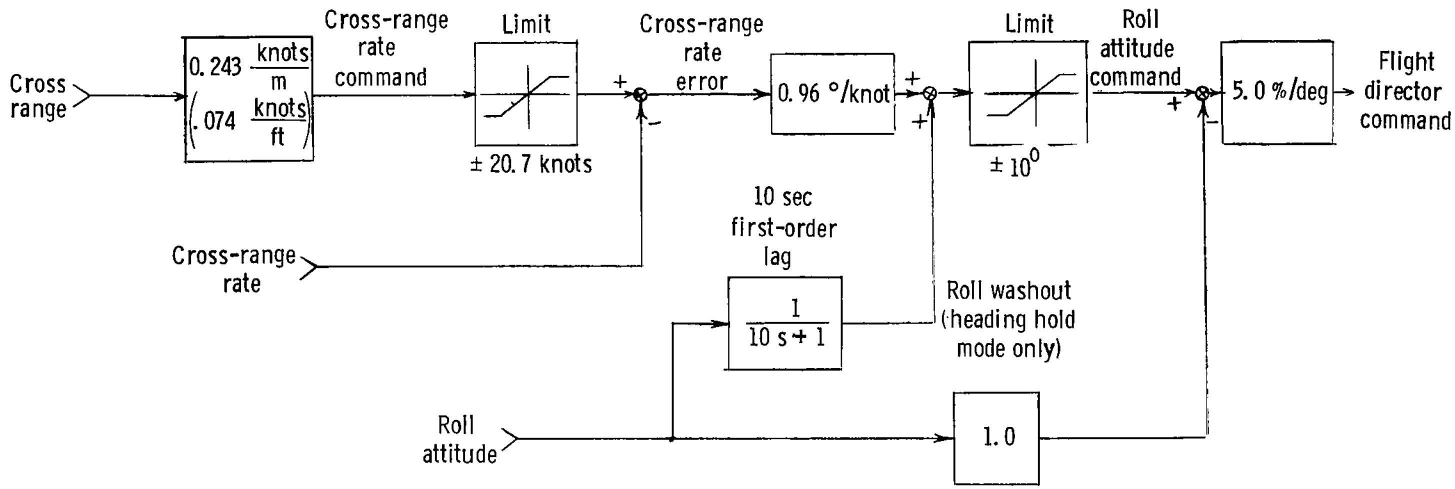
(b) Altitude profile.

Figure 4.- Nominal range-rate and altitude profiles.



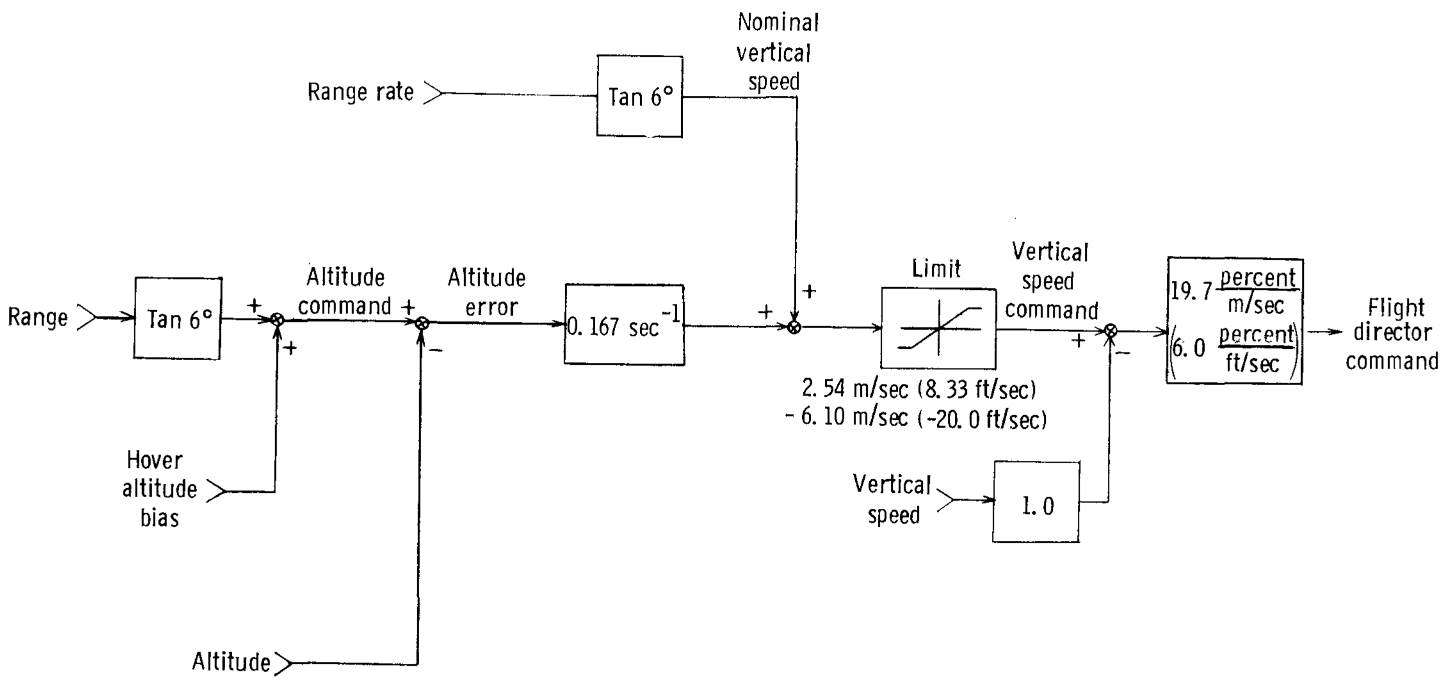
(a) Pitch command.

Figure 5.- Flight director control laws.



(b) Roll command.

Figure 5.- Continued.



(c) Collective command.

Figure 5.- Concluded.

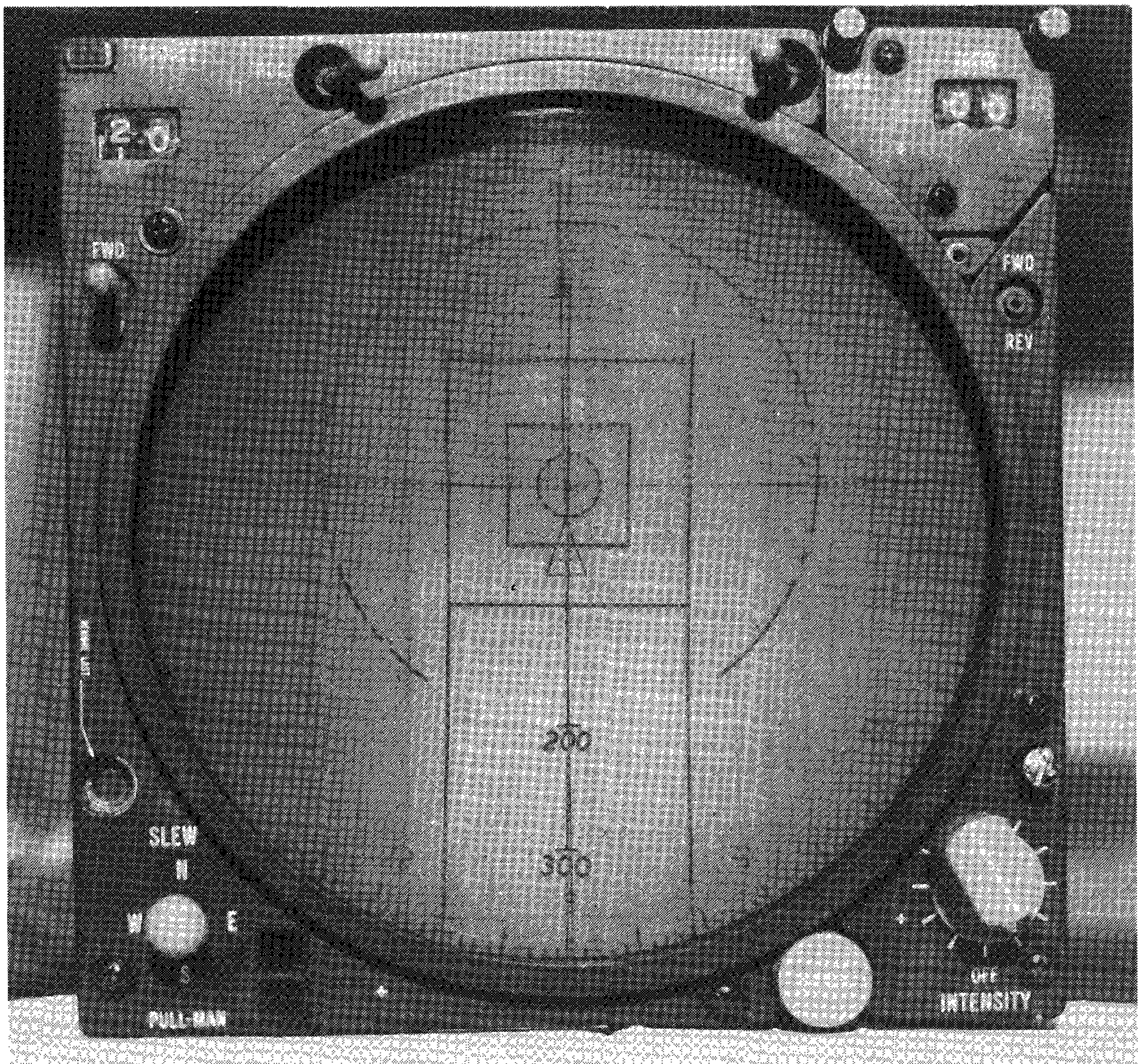


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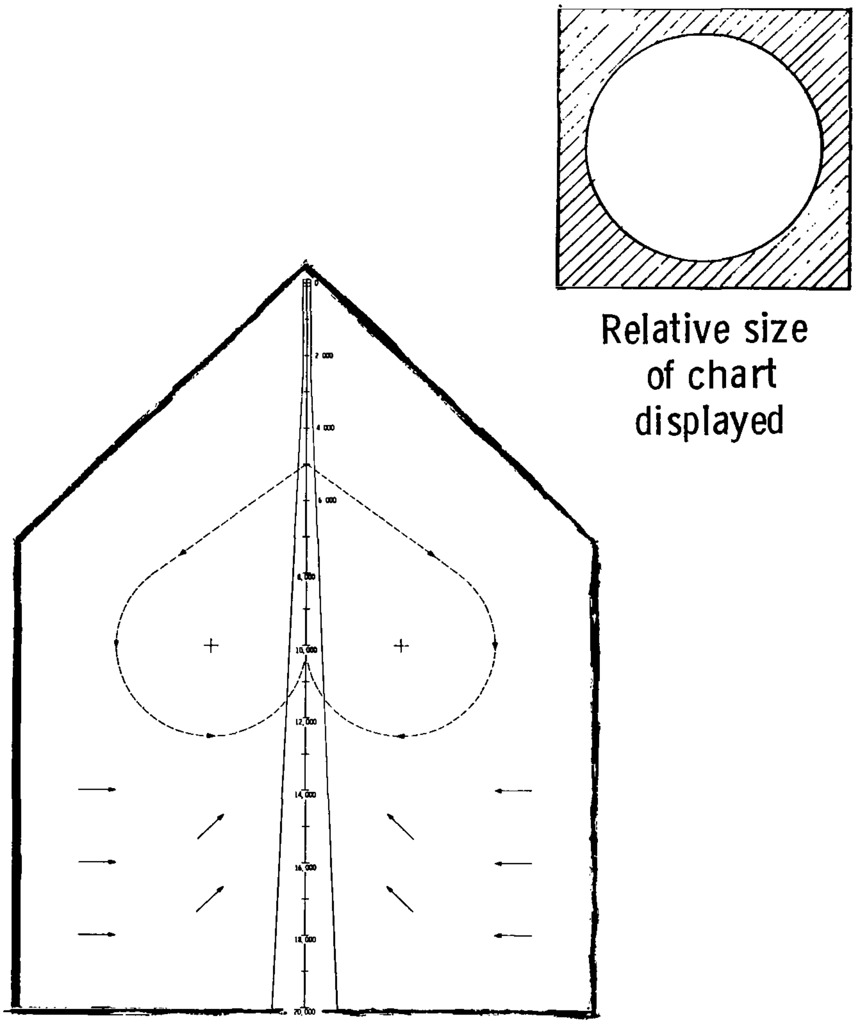
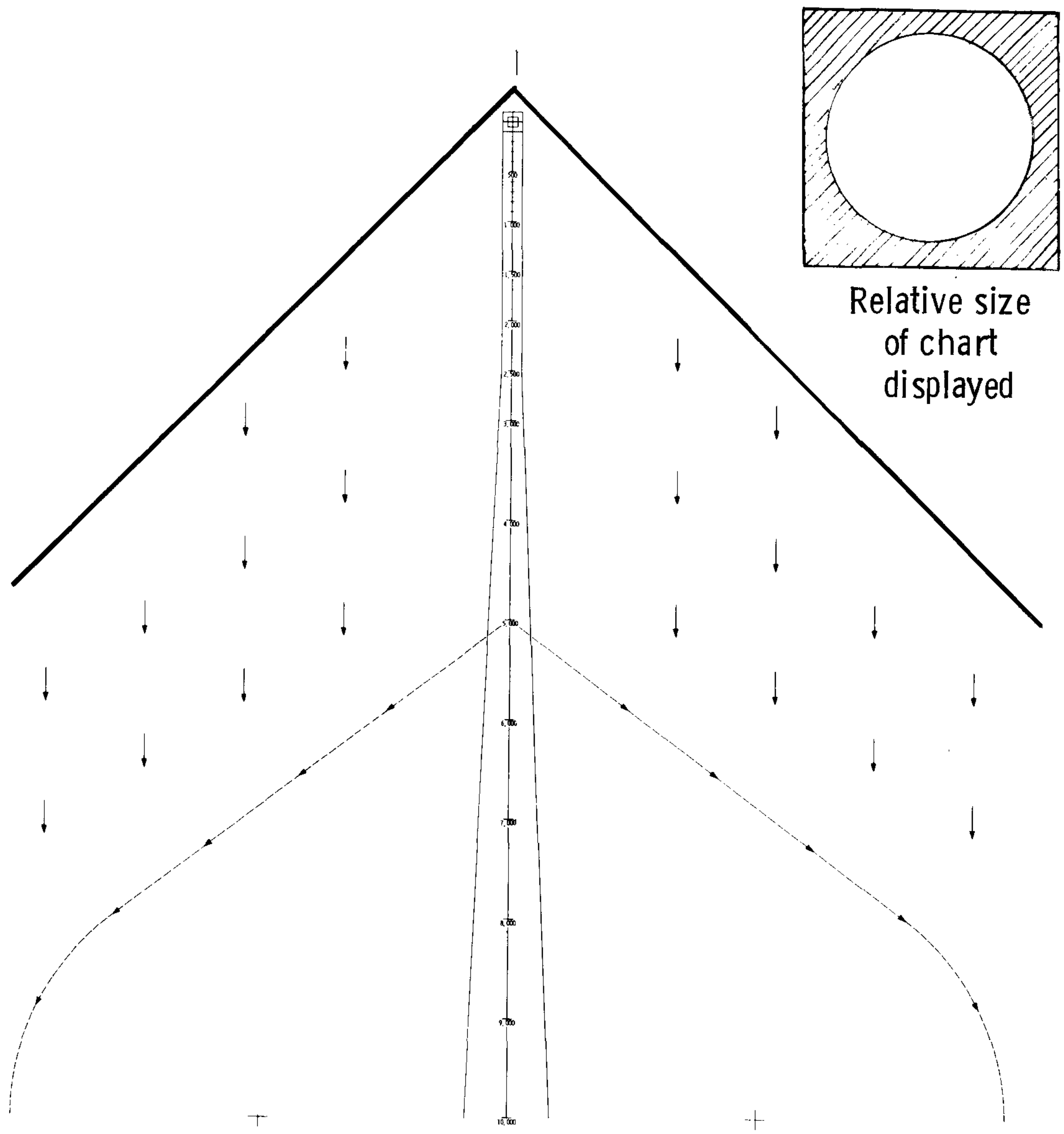
Figure 6.- Horizontal situation display.



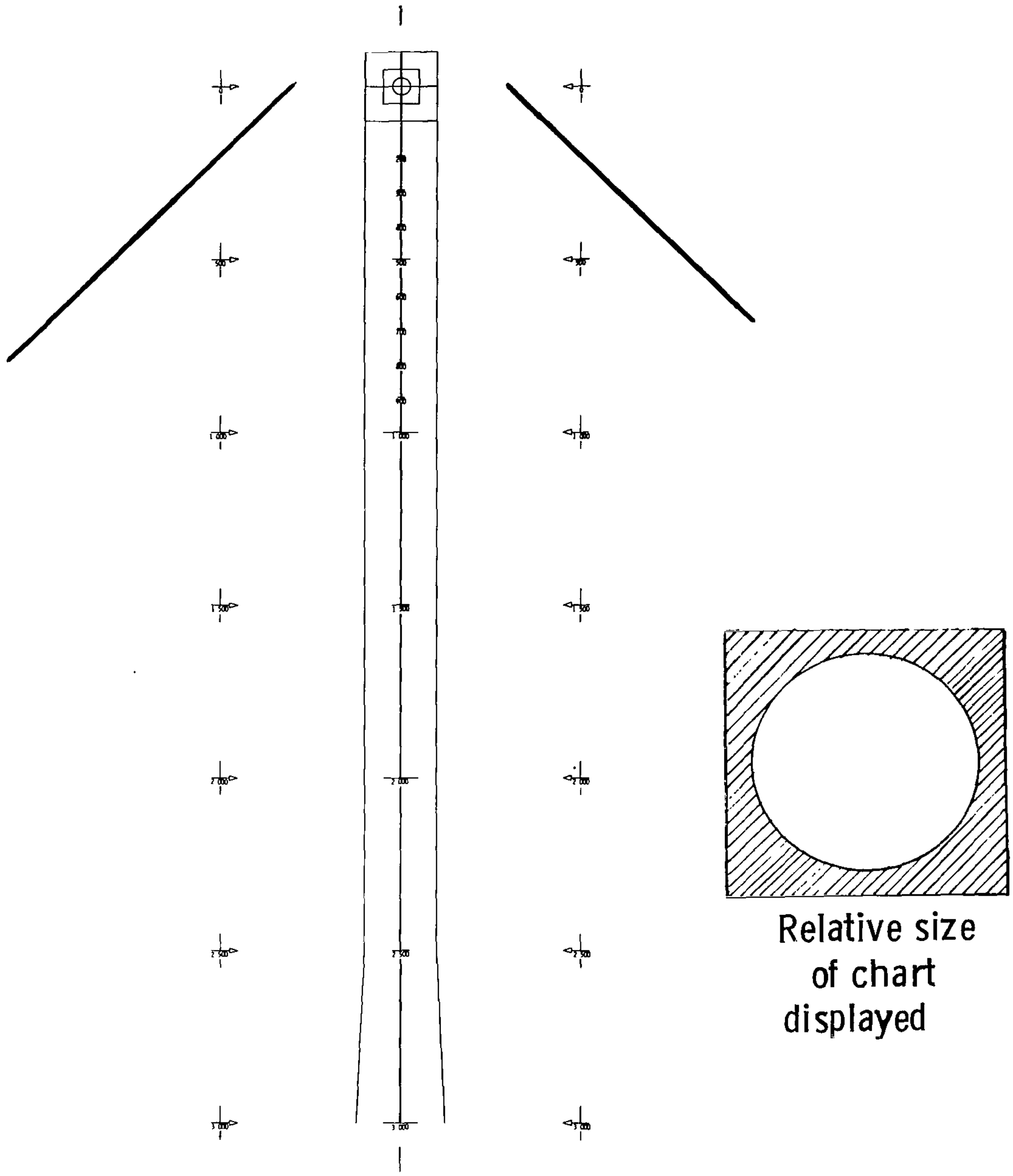
(a) Coarse scale.

Figure 7.- Horizontal situation display charts.



(b) Medium scale.

Figure 7.- Continued.



(c) Fine scale.

Figure 7.- Concluded.

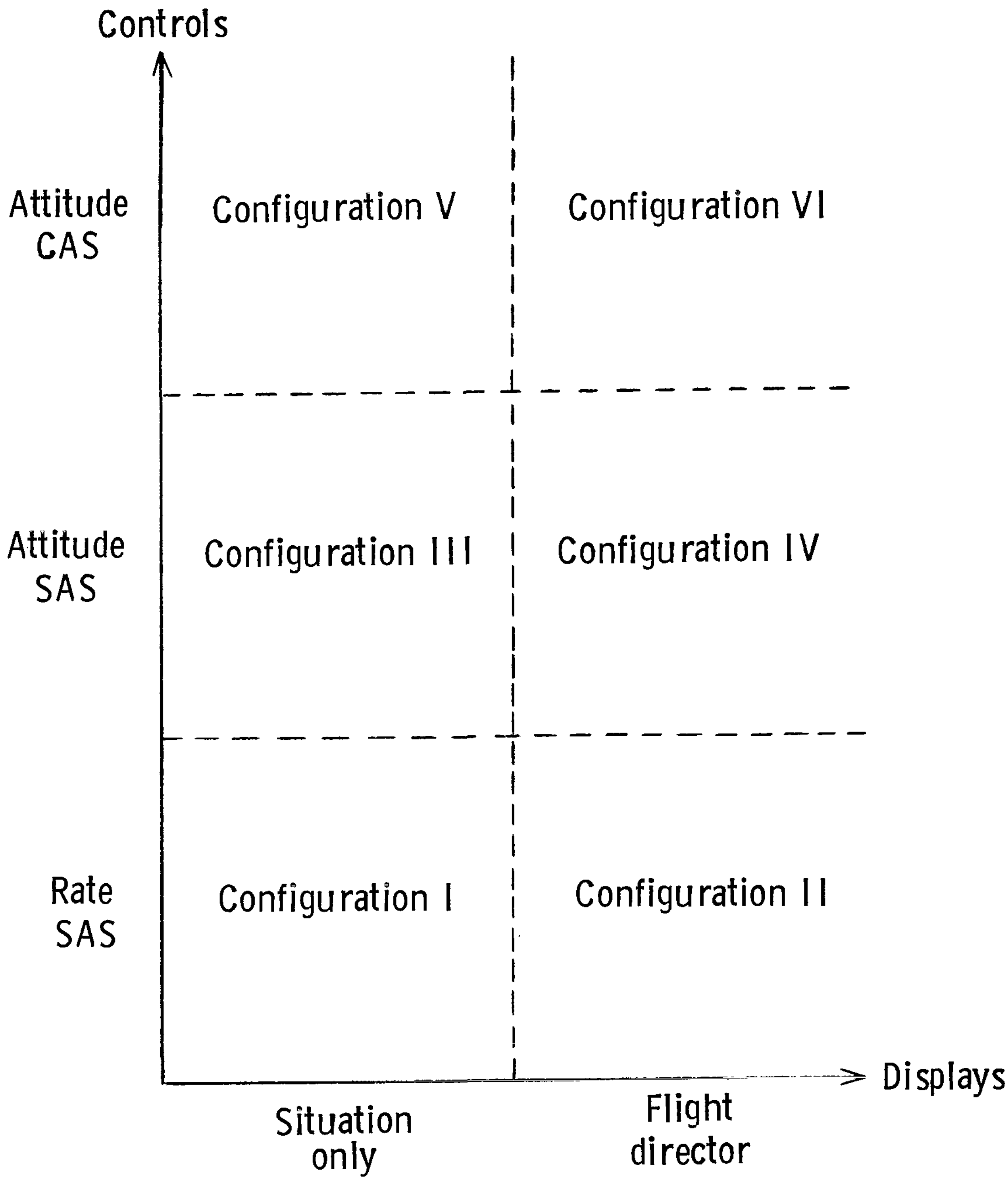
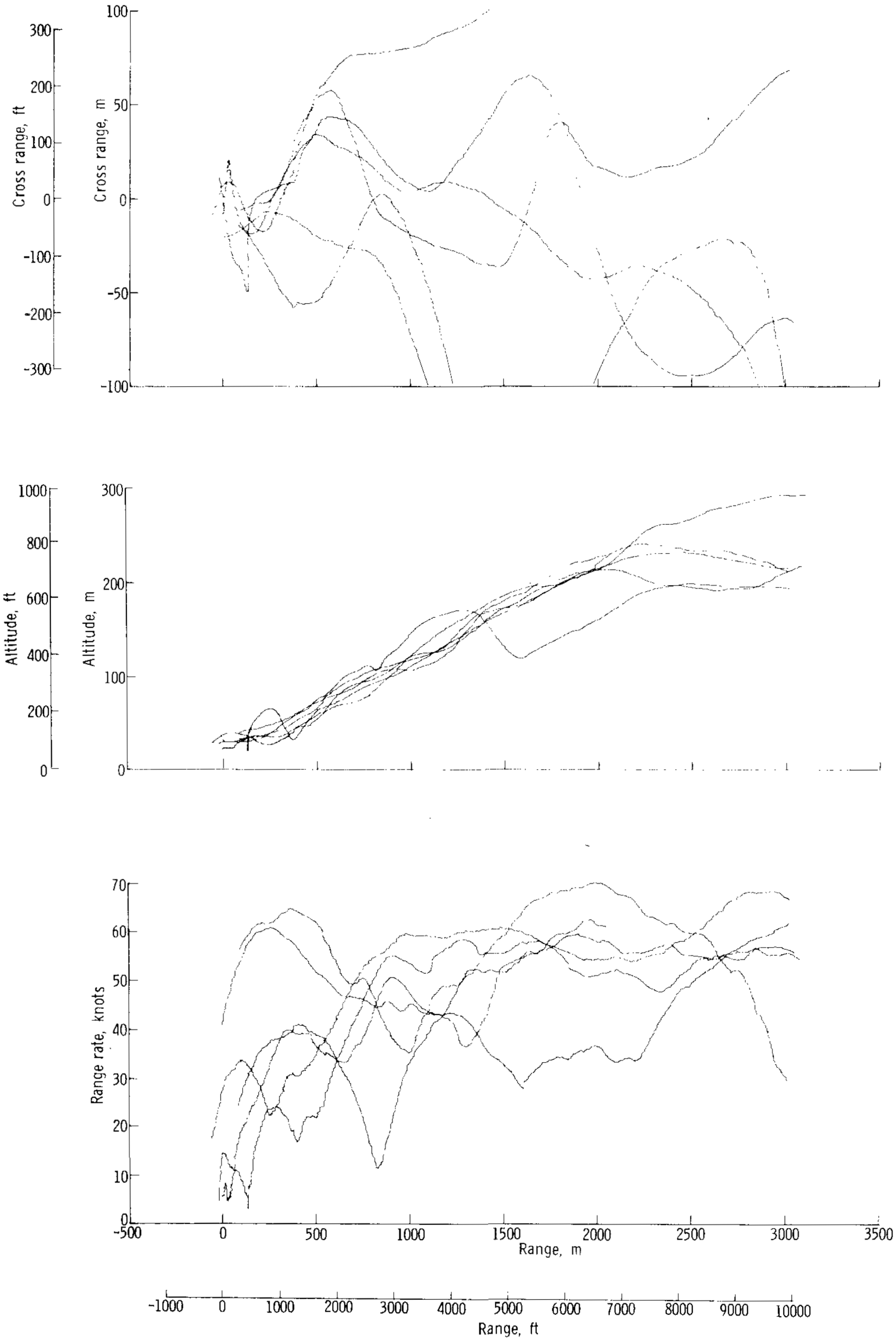
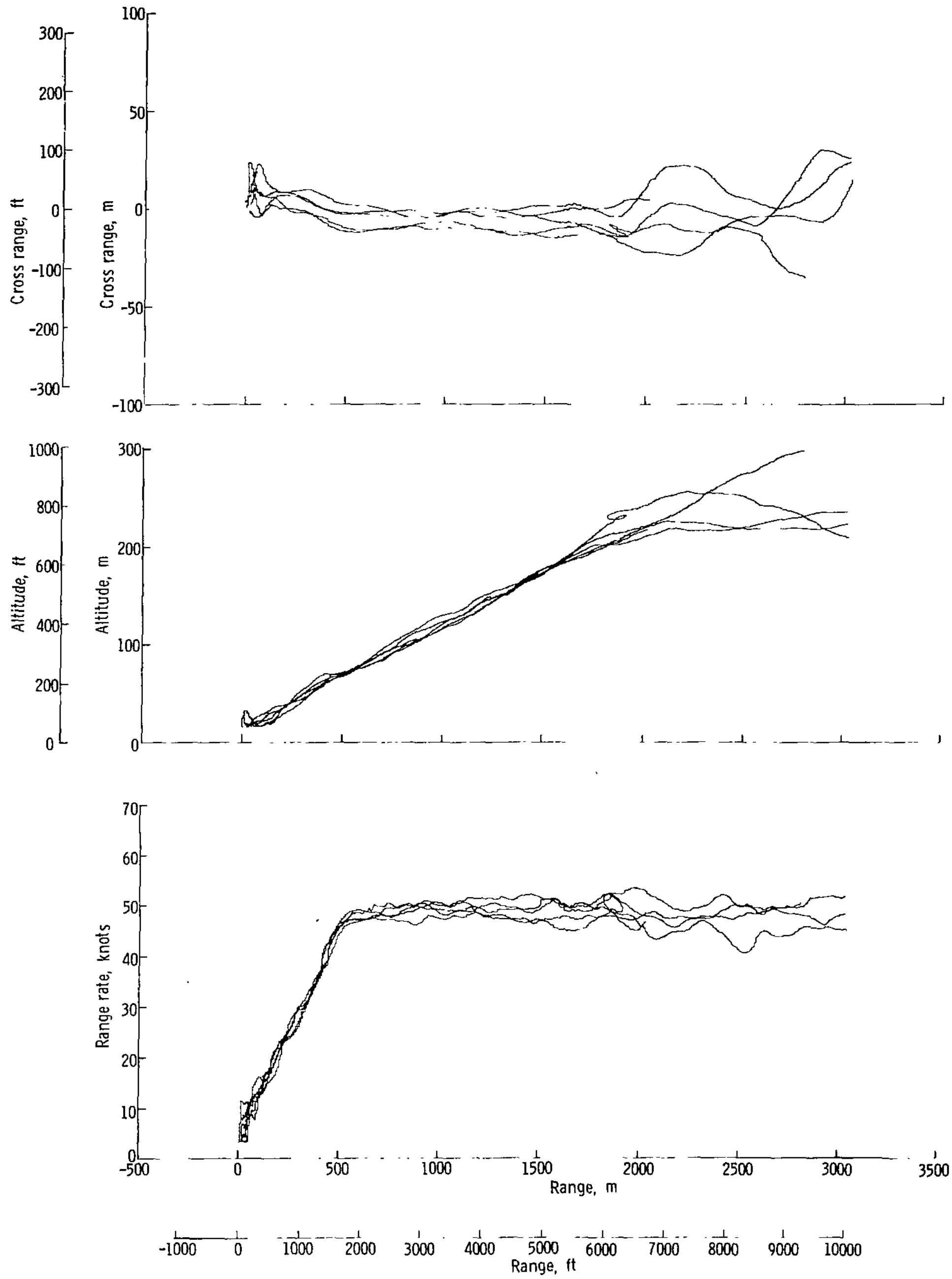


Figure 8.- Control and display configurations.



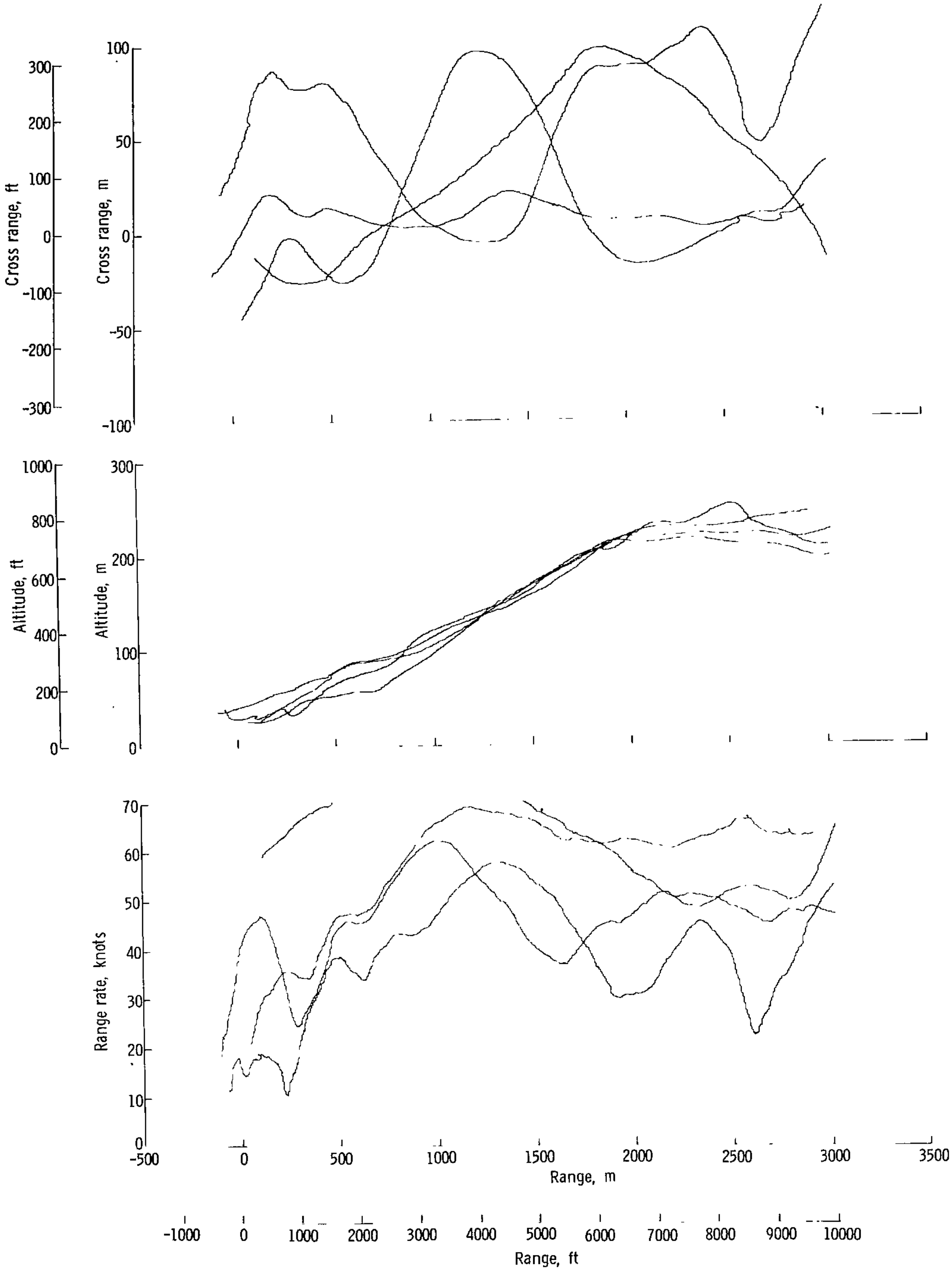
(a) Rate SAS and situation only.

Figure 9.- Approach performance.



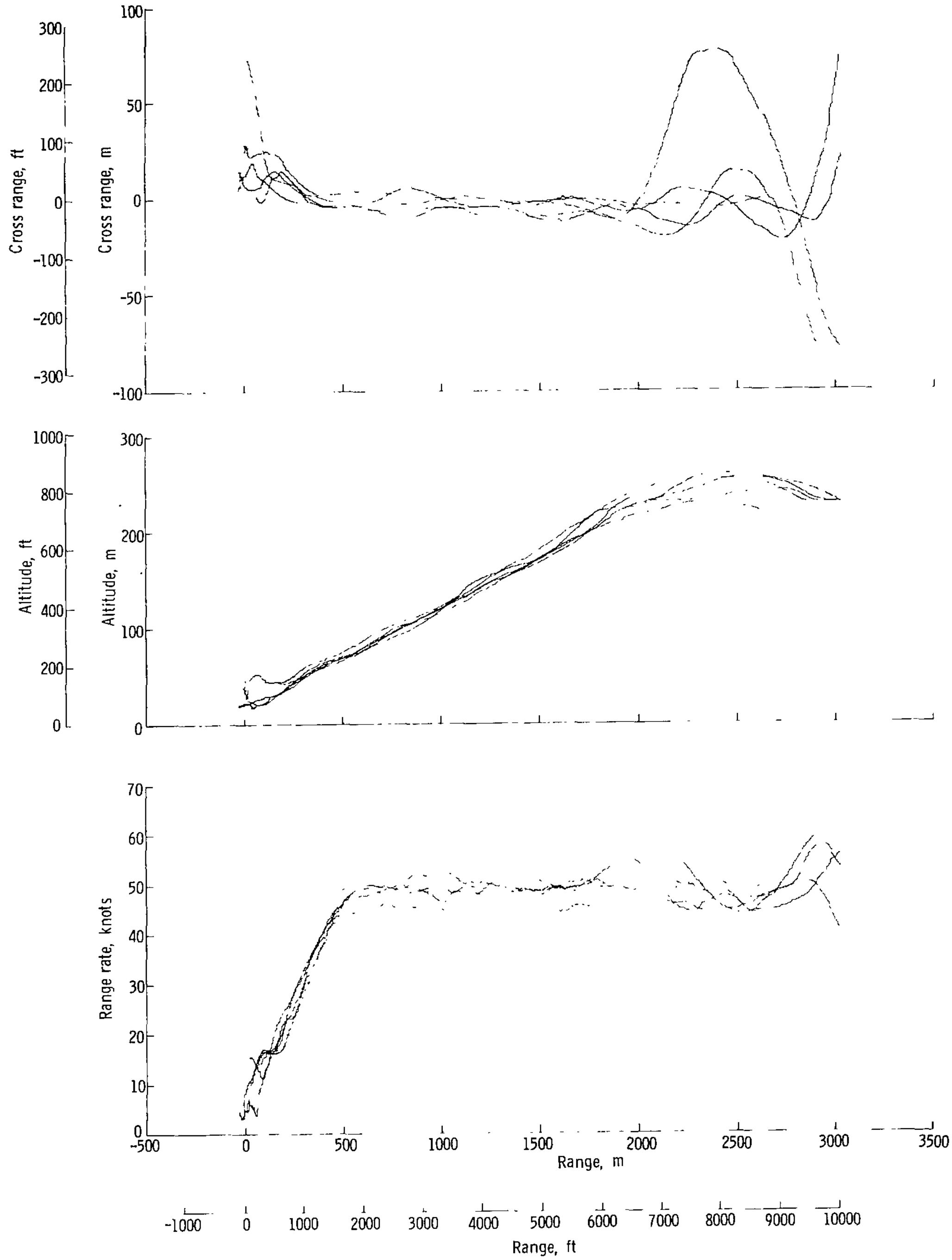
(b) Rate SAS and flight director.

Figure 9.- Continued.



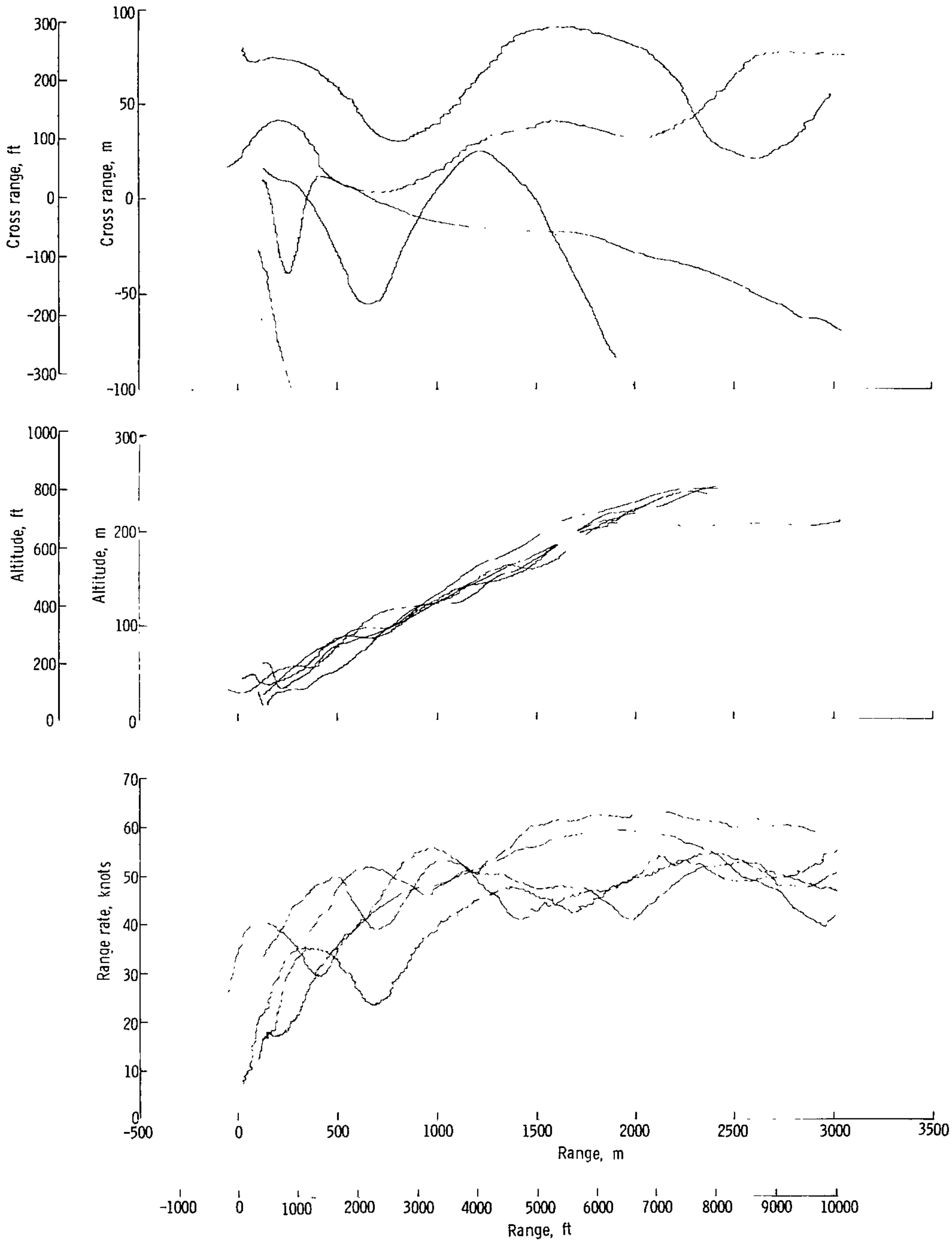
(c) Attitude SAS and situation only.

Figure 9.- Continued.



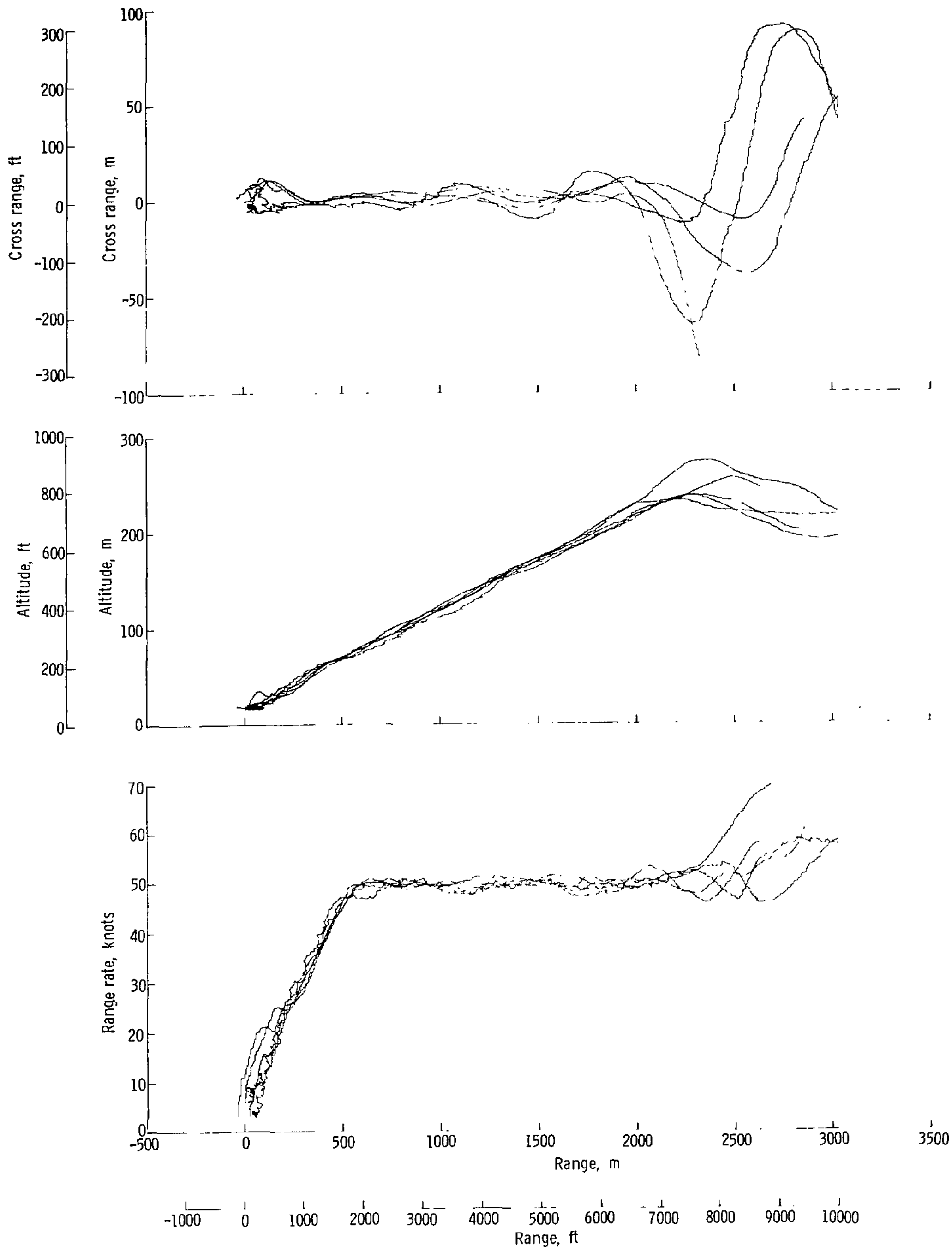
(d) Attitude SAS and flight director.

Figure 9.- Continued.



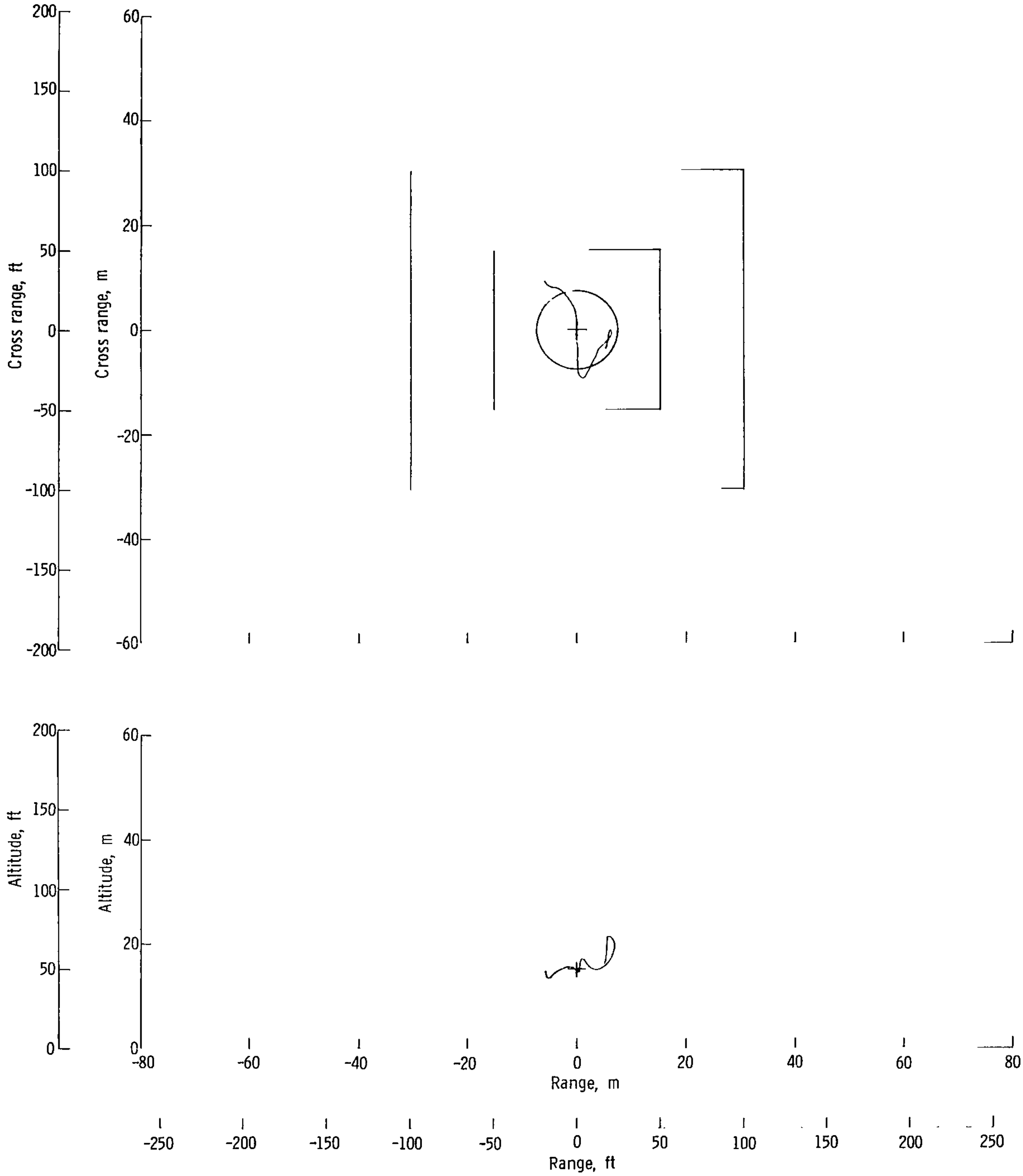
(e) Attitude CAS and situation only.

Figure 9.- Continued.



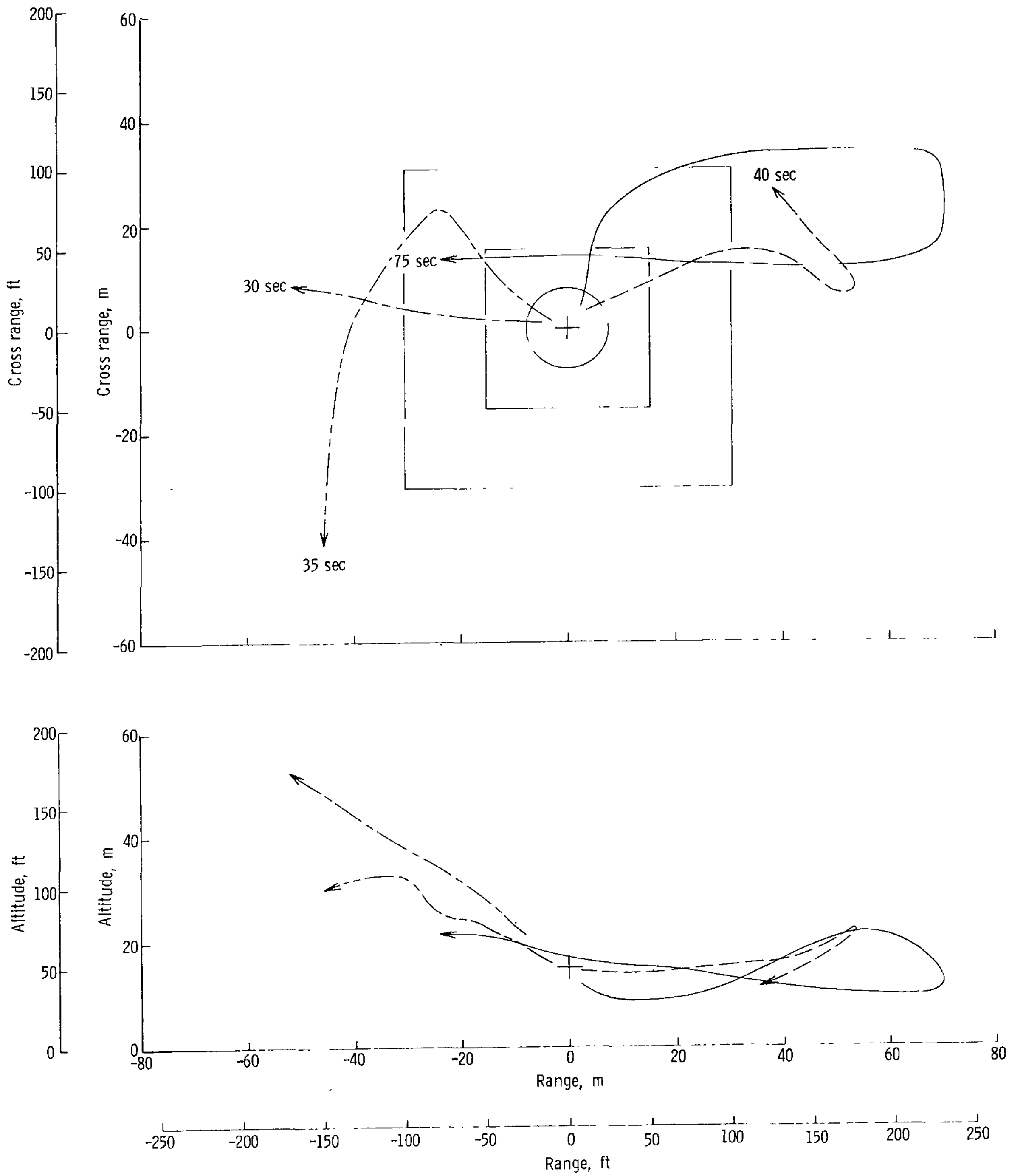
(f) Attitude CAS and flight director.

Figure 9.- Concluded.



(a) Flight director display. Length of data run, 56 sec.

Figure 10.- Hovering performance.



(b) Situation only display. Times indicate how long each run lasted after the flight director commands were removed.

Figure 10.- Concluded.

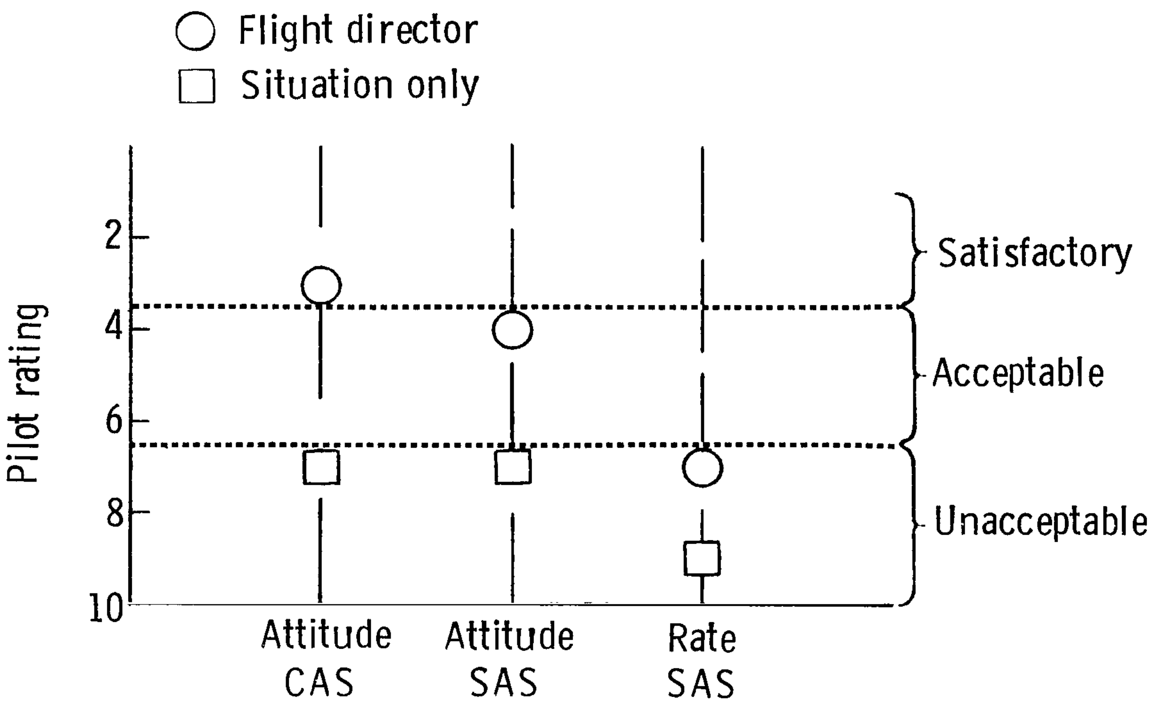


Figure 11.- Pilot ratings for approach task including deceleration and hover.

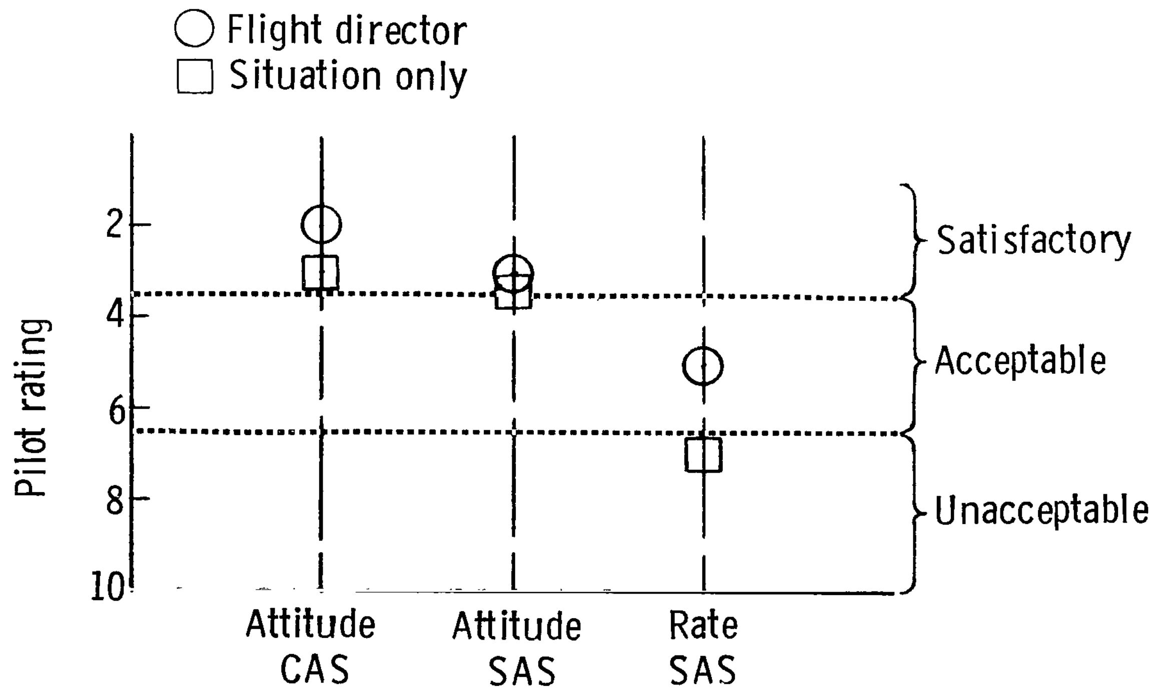
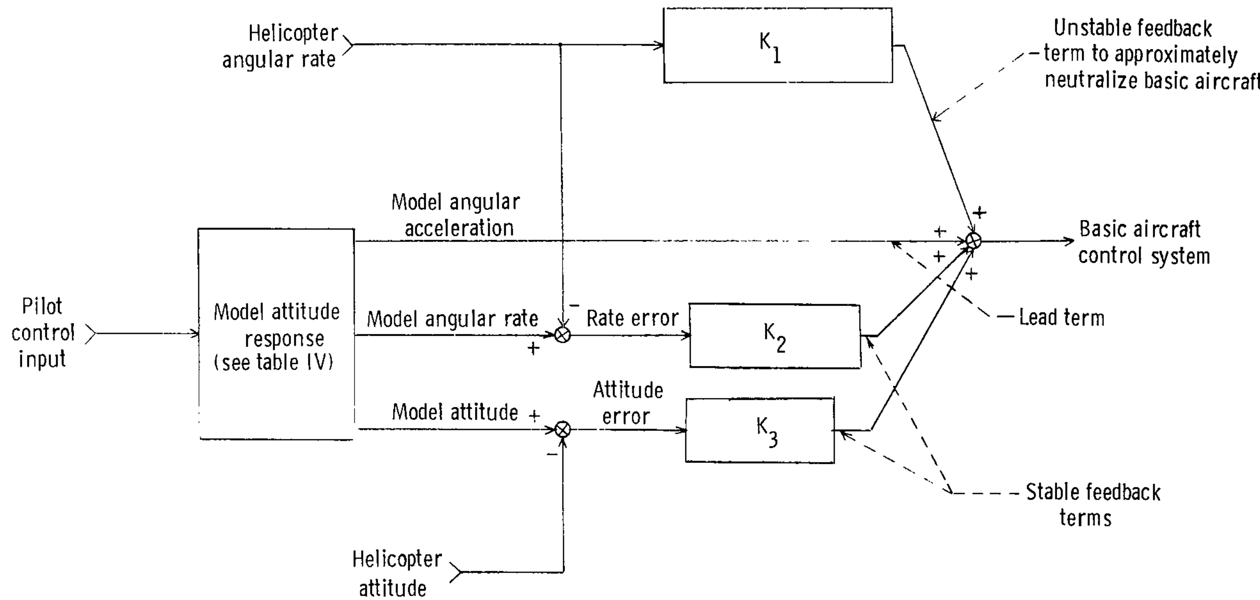


Figure 12.- Pilot ratings for approach task excluding deceleration and hover.



	Pitch	Roll
K_1, $\frac{cm}{deg/sec}$ $\left(\frac{in.}{deg/sec}\right)$	0.072 (0.028)	0.084 (0.033)
K_2, $\frac{cm}{deg/sec}$ $\left(\frac{in.}{deg/sec}\right)$	0.97 (0.38)	0.62 (0.24)
K_3, $\frac{cm}{deg}$ $\left(\frac{in.}{deg}\right)$	3.25 (1.28)	1.72 (0.68)

Figure 13.- Attitude CAS control system for pitch and roll.

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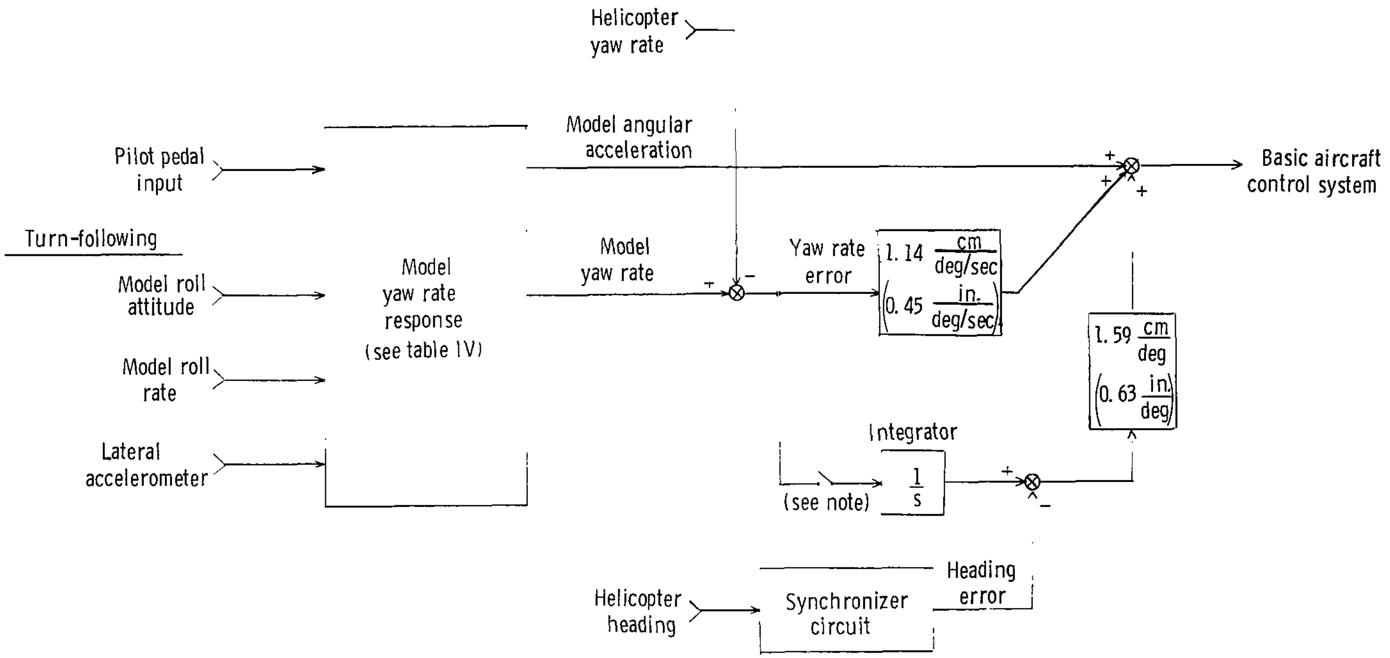

Figure 14.- Attitude CAS control system for yaw. Switch opens and synchronizer circuit defines a heading error when heading-hold mode is selected and pedals are within deadband.

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